Instrumental backgrounds in the LUX-ZEPLIN (LZ) detector

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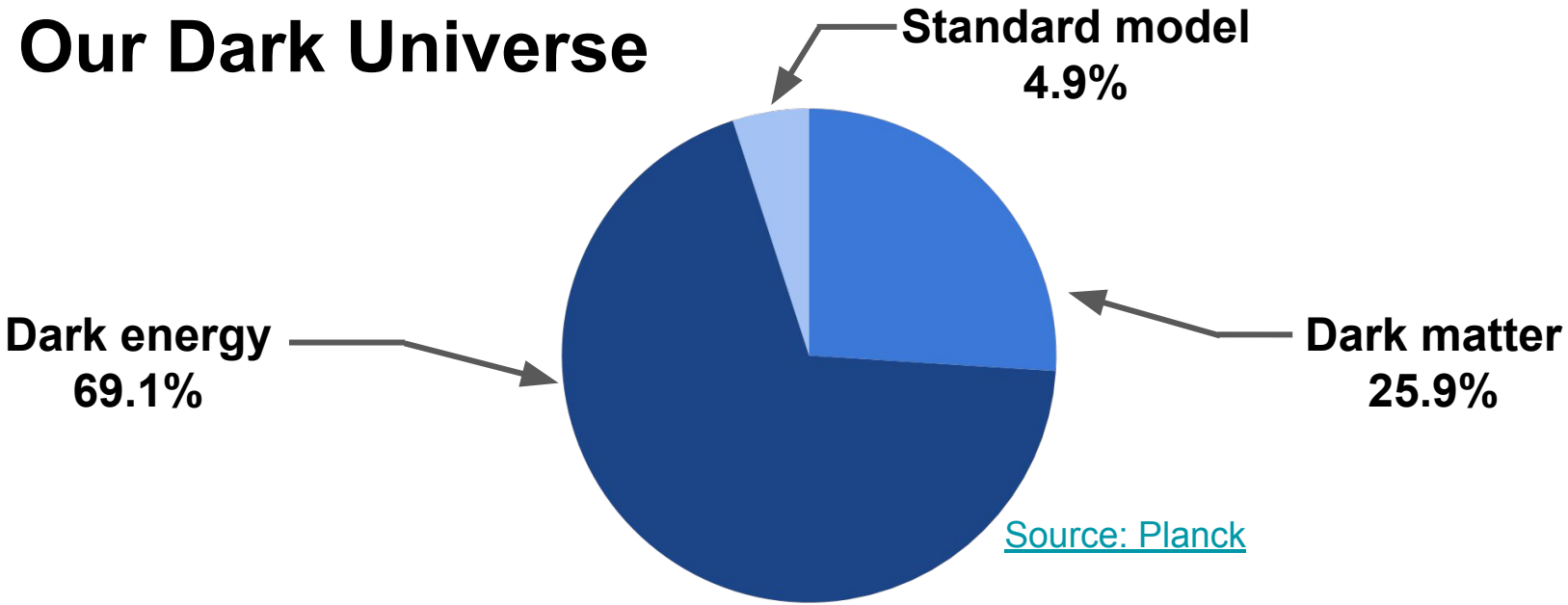
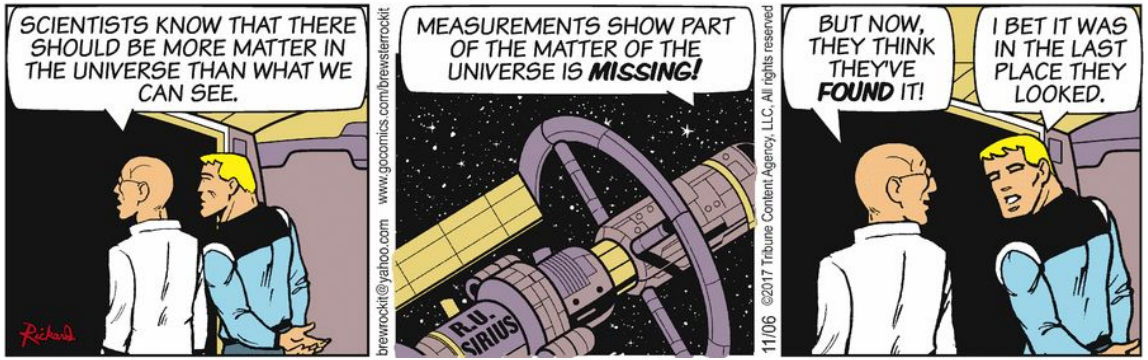
Instrumentation Seminar
Fermilab
11/6/20

Stanford University
KIPAC
KAVLI INSTITUTE FOR PARTICLE ASTROPHYSICS & COSMOLOGY
SLAC

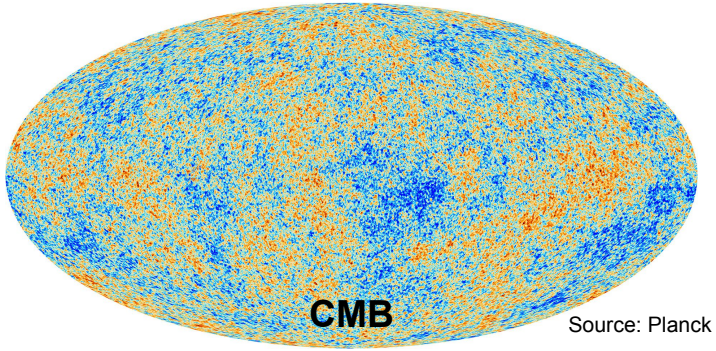
Our Dark Universe



Source: Planck



Dark matter in astrophysics: “The Usual Suspects”



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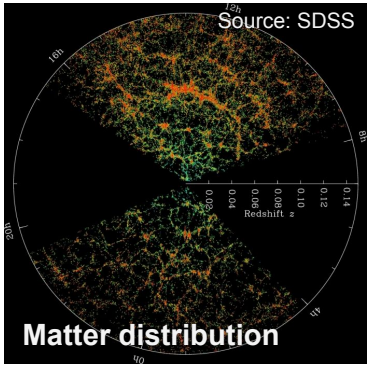
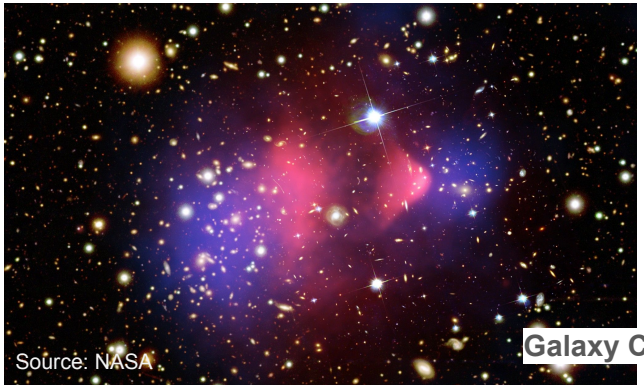
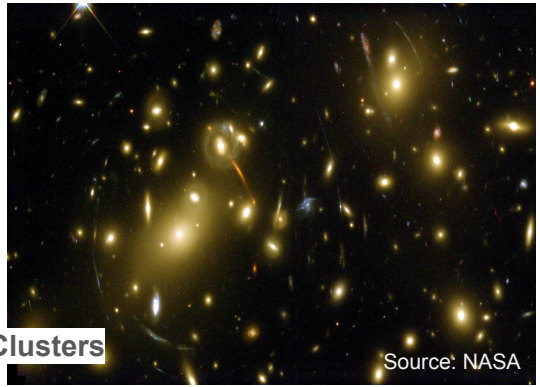
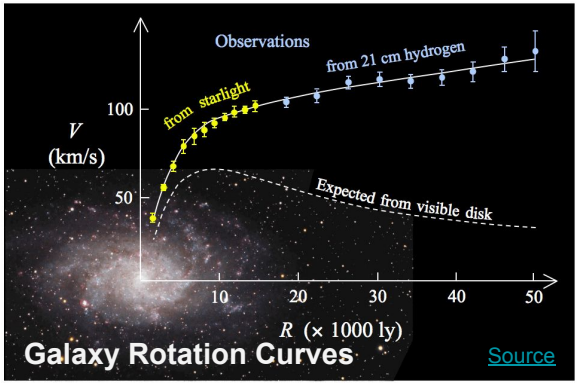


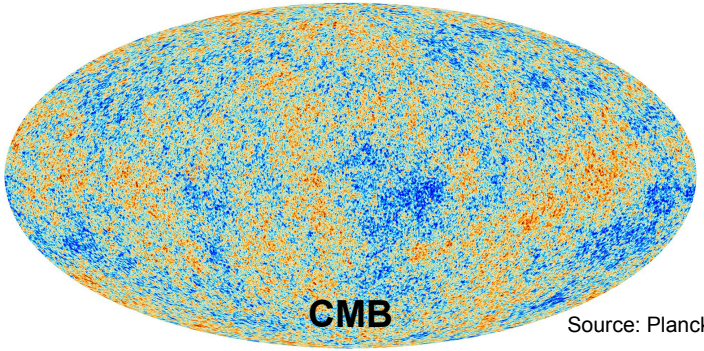




Galaxy Clusters



Dark matter in astrophysics: “The Usual Suspects”



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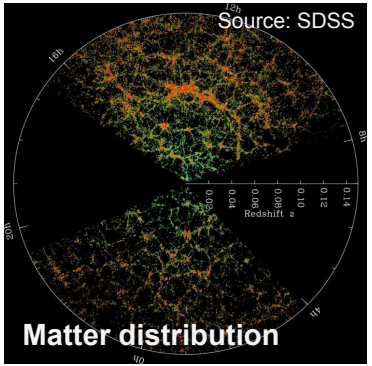

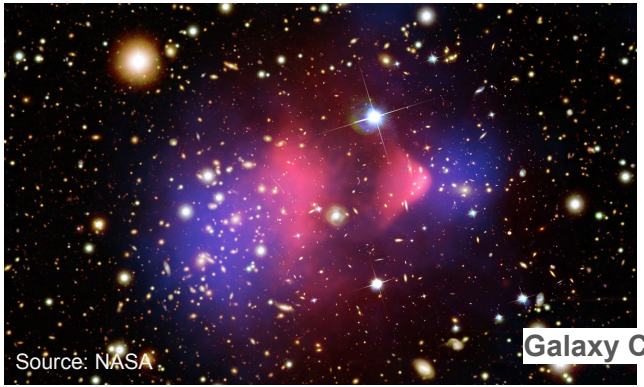

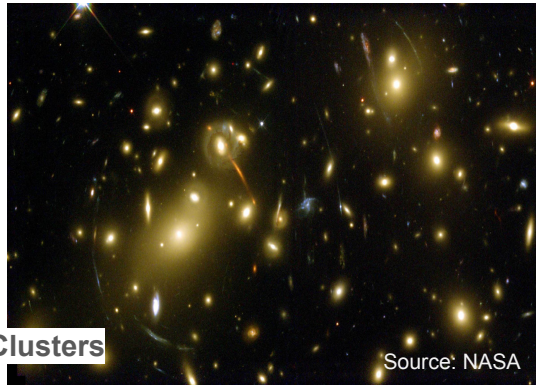

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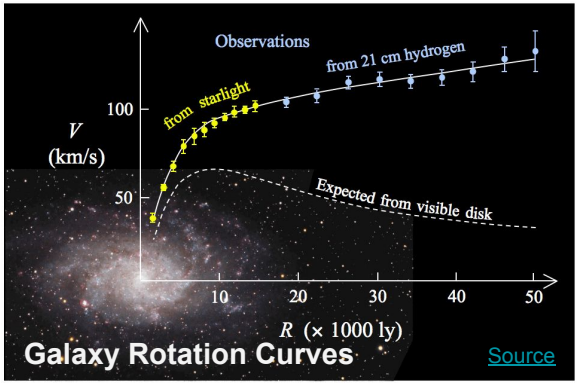


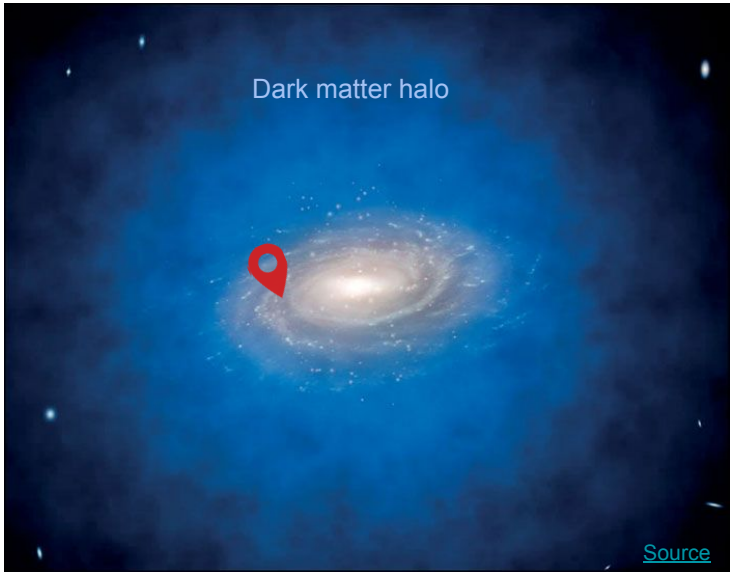
“While the observational evidence for dark matter is exceptionally convincing, our current level of ignorance of the basic properties of dark matter is remarkable”

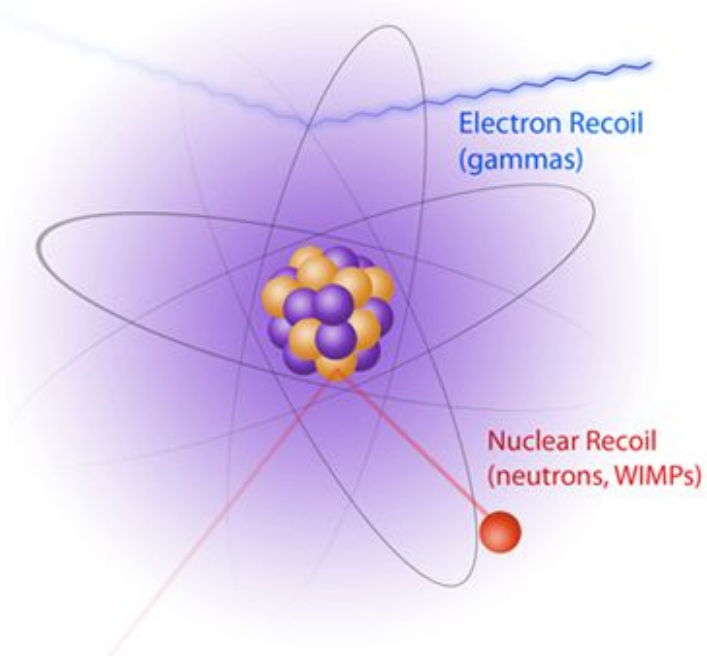
(Briefing Book for European Strategy for Particle Physics Update 2020)

One model: Weakly Interacting Massive Particles

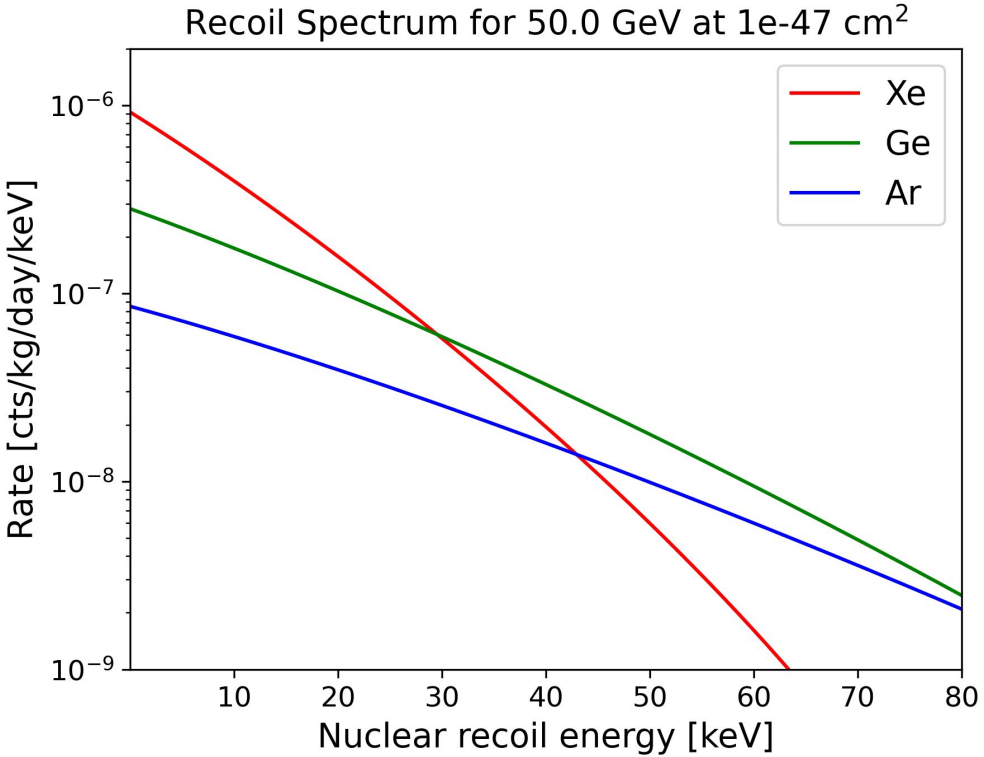
Historically favored model for dark matter that interacts near the weak scale

Goal: Detect nuclear recoils from galactic DM elastically scattering off nuclei





Detecting WIMPs



Low energy O(10keV) atomic recoils

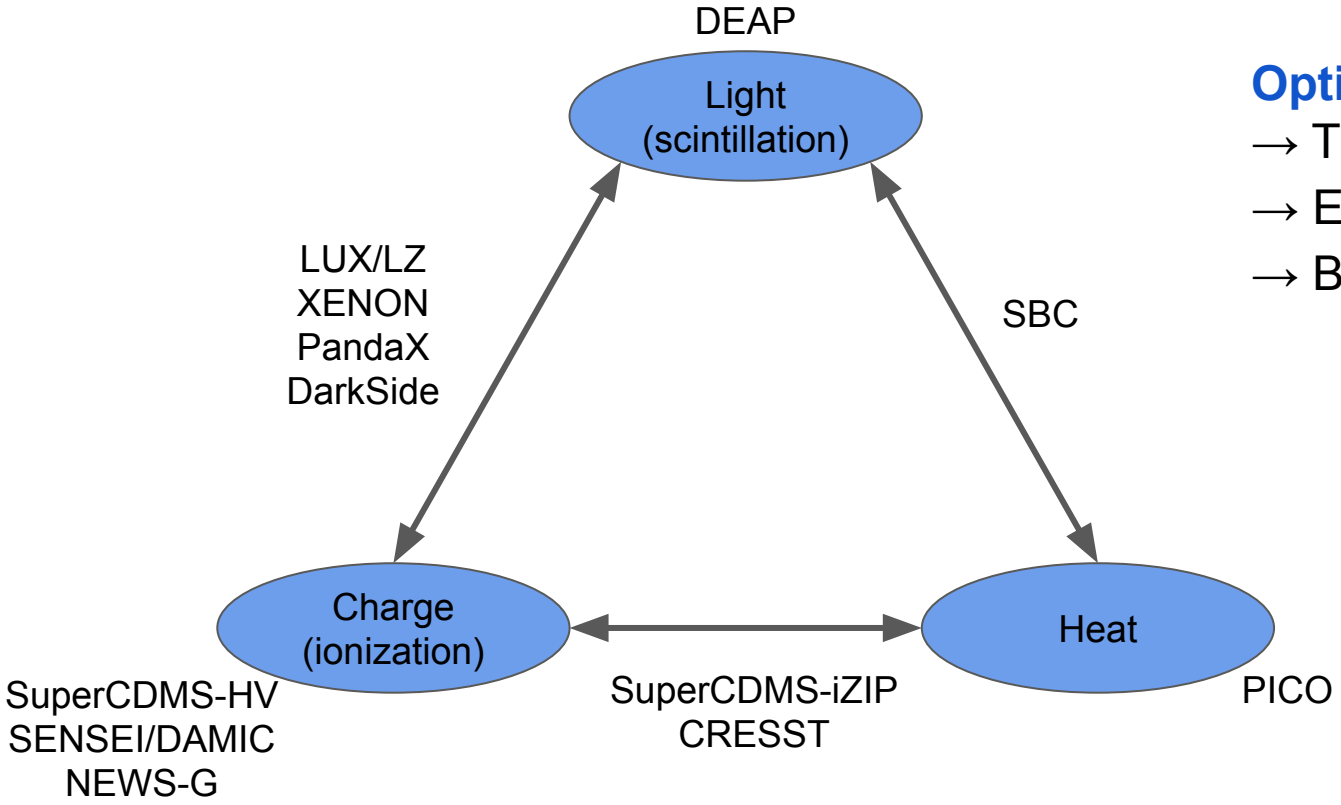
→ **Low energy threshold**

Low event rate (handful per year)

→ **Large exposure**

→ **Low background**

WIMP Scattering Detection Pathways



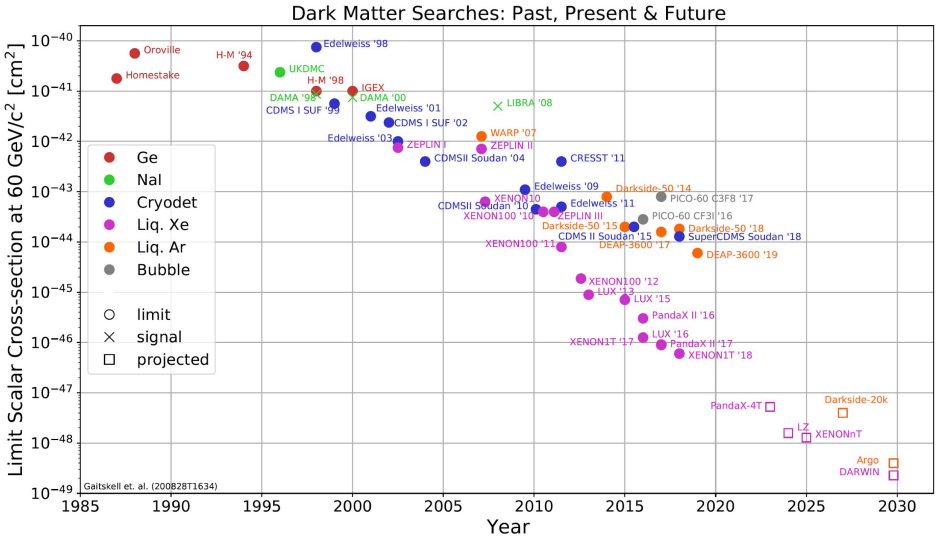
Optimizing between:

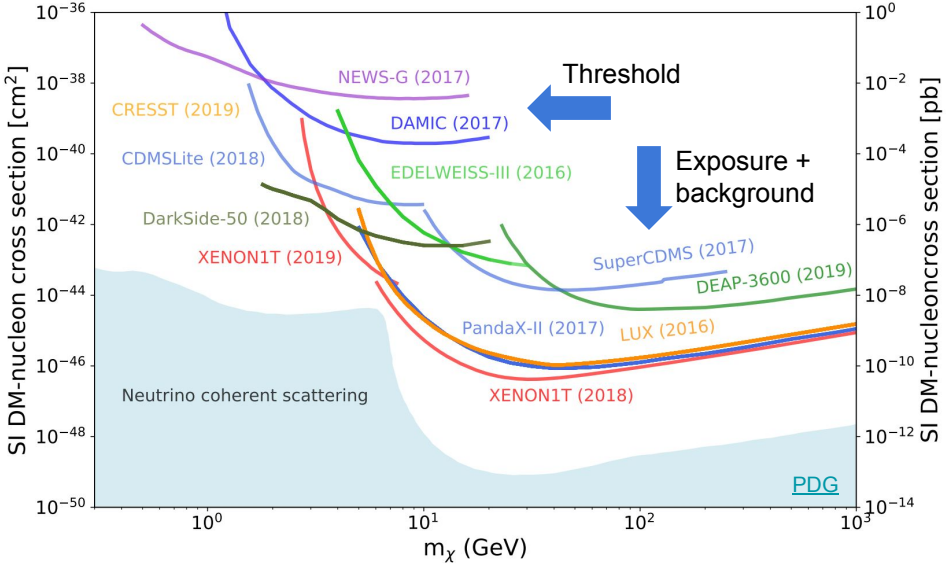
→ Threshold

→ Exposure

→ Background

Xenon: Leading the hunt for heavy WIMPs



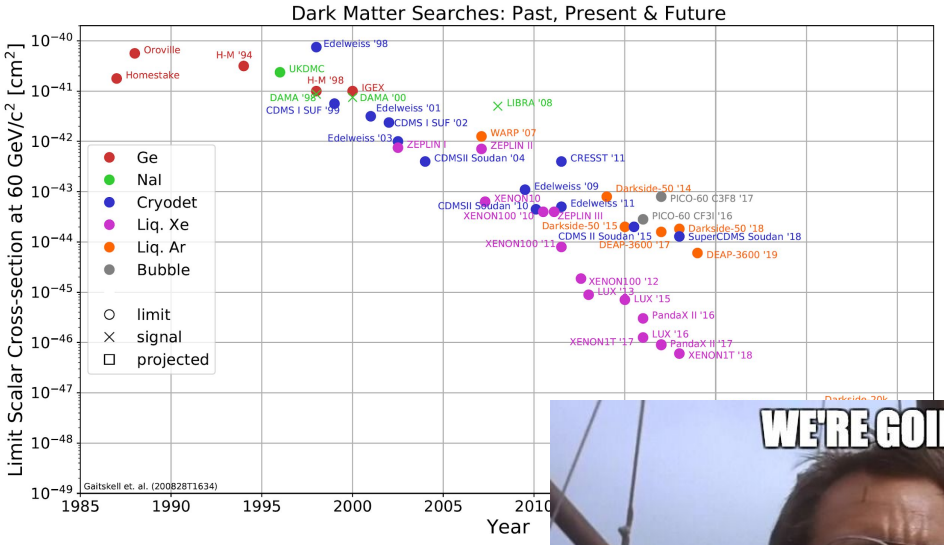


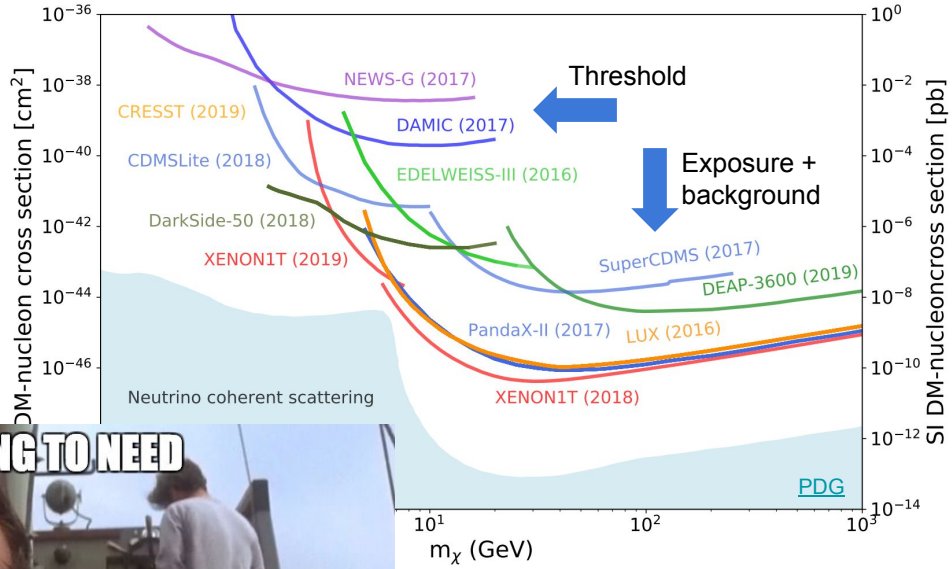
Good threshold, but

GREAT scalability + background discrimination/reduction

To the neutrino floor!

Xenon: Leading the hunt for heavy WIMPs





GREAT …n/reduction

The LUX-ZEPLIN experiment

1. Design
2. Current status

LZ Collaboration - July 2019

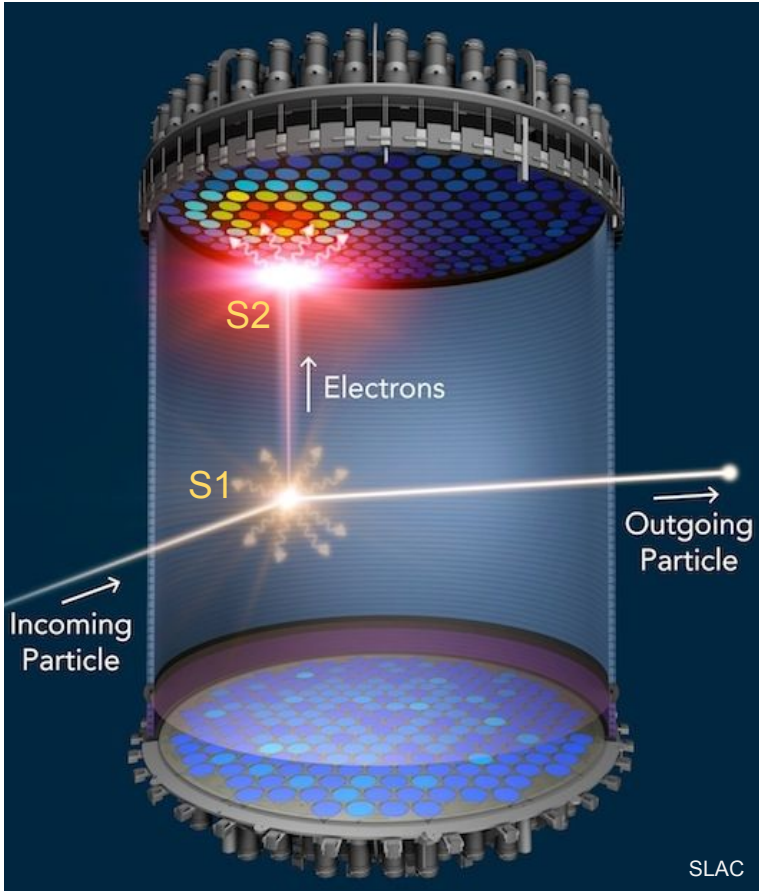
5 countries, 36 institutions, ~250 scientists/engineers

IBS-CUP (Korea)
LIP Coimbra (Portugal)
MEPhI (Russia)
Imperial College London (UK)
Royal Holloway University of London (UK)
STFC Rutherford Appleton Lab (UK)
University College London (UK)
University of Bristol (UK)
University of Edinburgh (UK)
University of Liverpool (UK)
University of Oxford (UK)
University of Sheffield (UK)

Black Hill State University (US)
Brandeis University (US)
Brookhaven National Lab (US)
Brown University (US)
Fermi National Accelerator Lab (US)
Lawrence Berkeley National Lab (US)
Lawrence Livermore National Lab (US)
Northwestern University (US)
Pennsylvania State University (US)
SLAC National Accelerator Lab (US)
South Dakota School of Mines and Technology (US)
South Dakota Science and Technology Authority (US)

Texas A&M University (US)
University at Albany (US)
University of Alabama (US)
University of California, Berkeley (US)
University of California, Davis (US)
University of California, Santa Barbara (US)
University of Maryland (US)
University of Massachusetts (US)
University of Michigan (US)
University of Rochester (US)
University of South Dakota (US)
University of Wisconsin – Madison (US)

Dual-phase time projection chambers (TPCs)



Sensitive to single quanta through:

- Scatters in the liquid produce **scintillation light (S1)** and ionization electrons
- Electrons drift to gas phase where they produce **electroluminescence (S2)**

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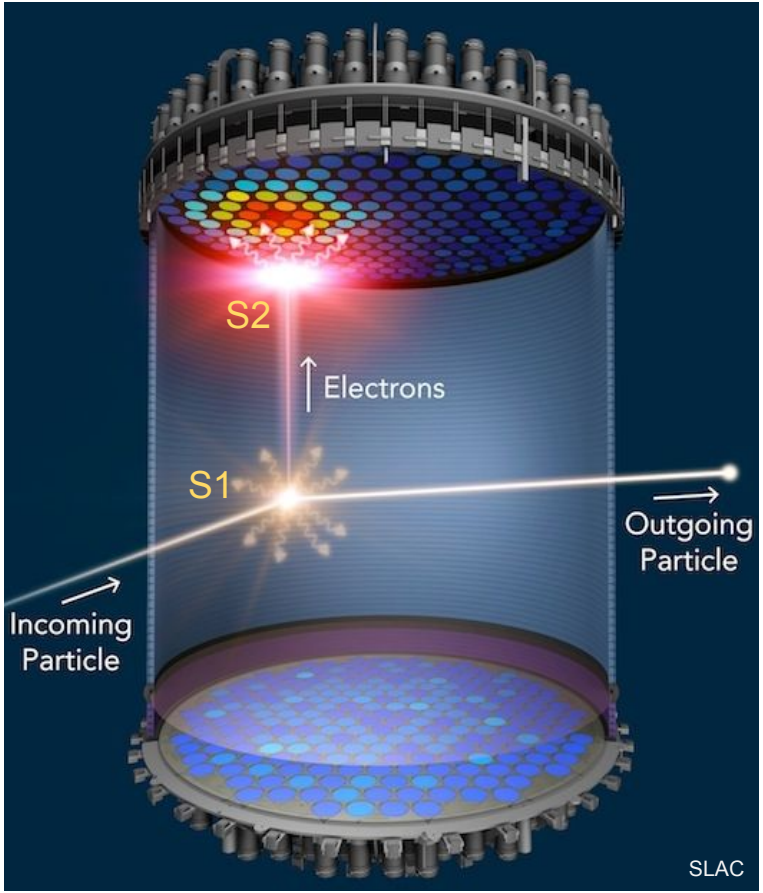

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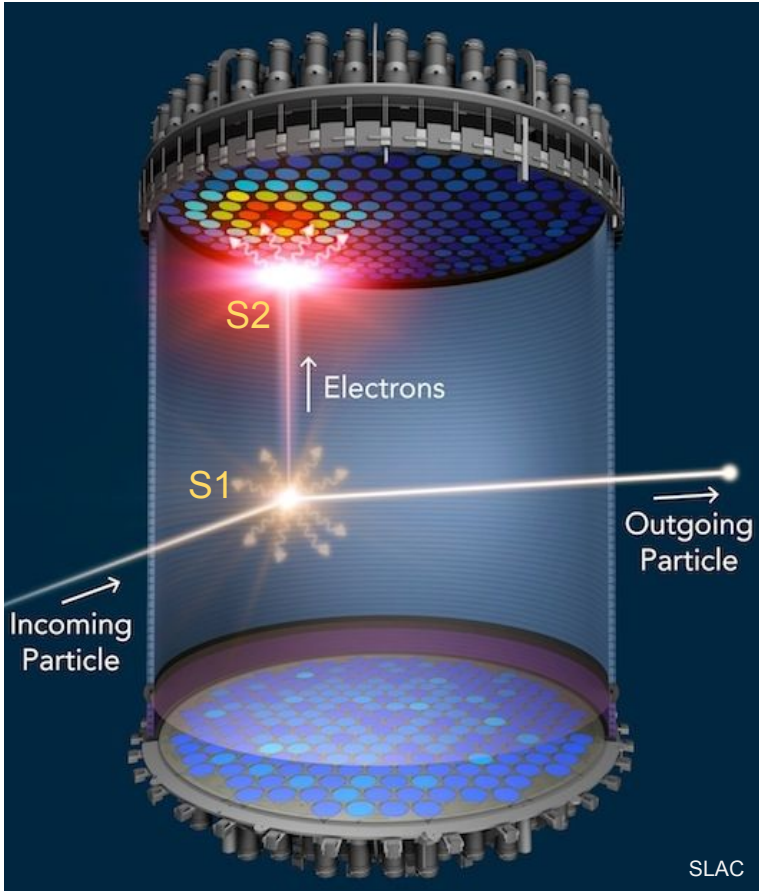
Reconstructed variables:

- Energy: S1 + S2
- 3D position: XY from S2, Z from drift time
- Particle ID: S2/S1 ratio

Dual-phase time projection chambers (TPCs)



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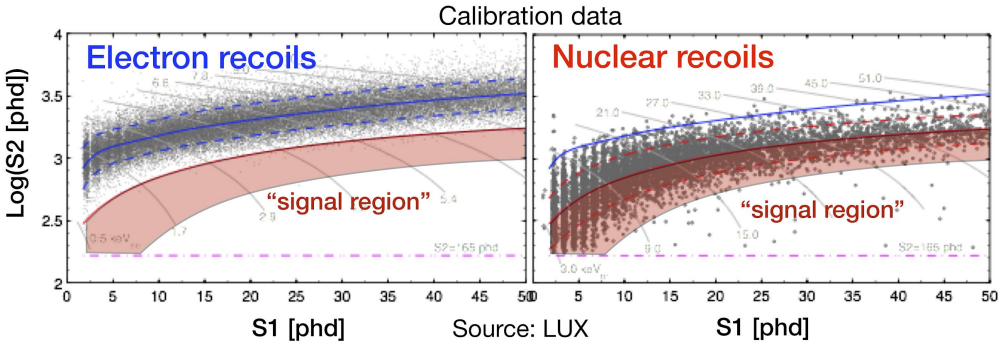


The LZ experiment

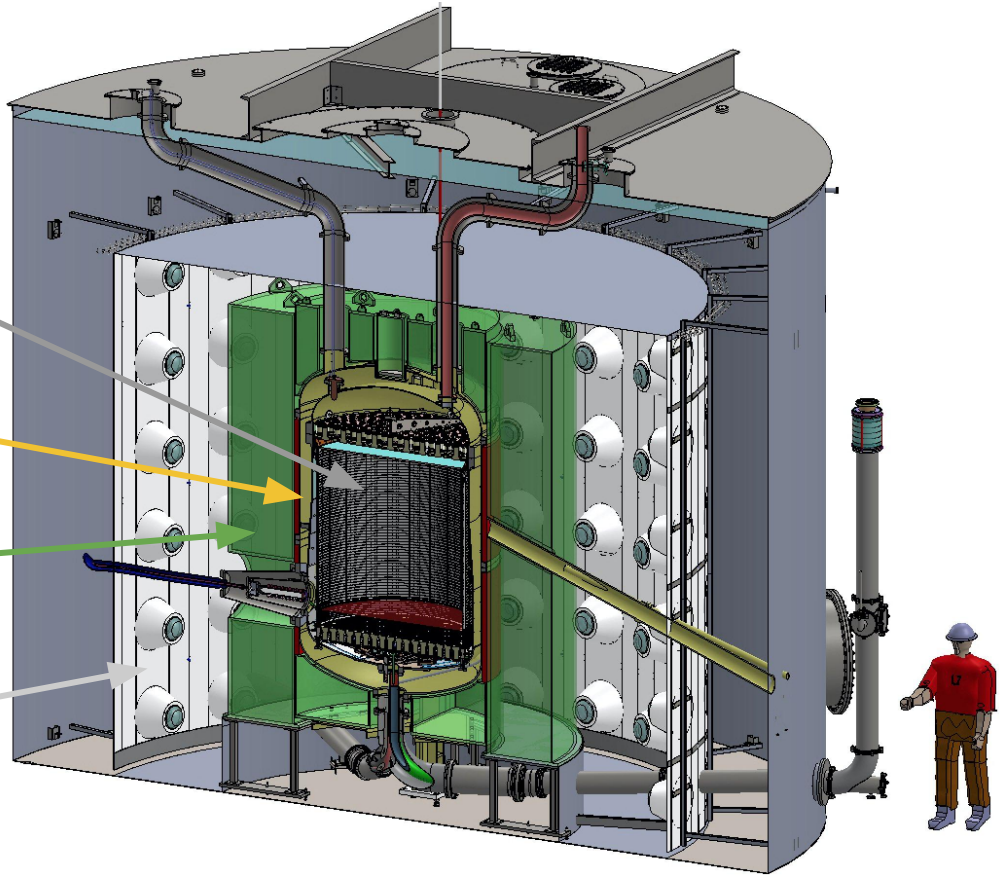
LZ TDR arXiv:1703.09144
LZ Detector arXiv:1910.09124

Nested detectors:

7t dual-phase Xe TPC

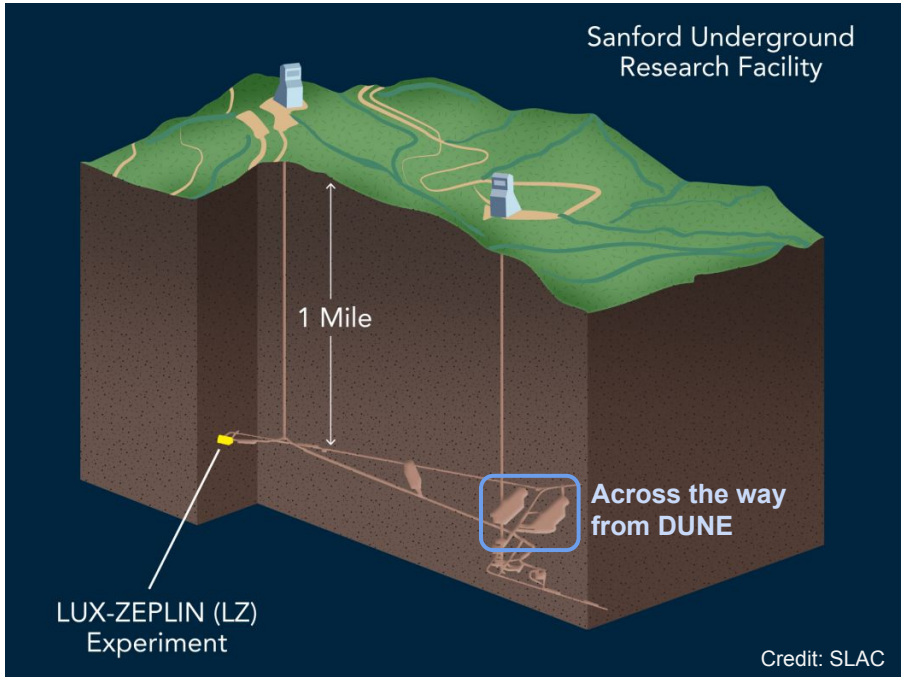
2t LXe skin region

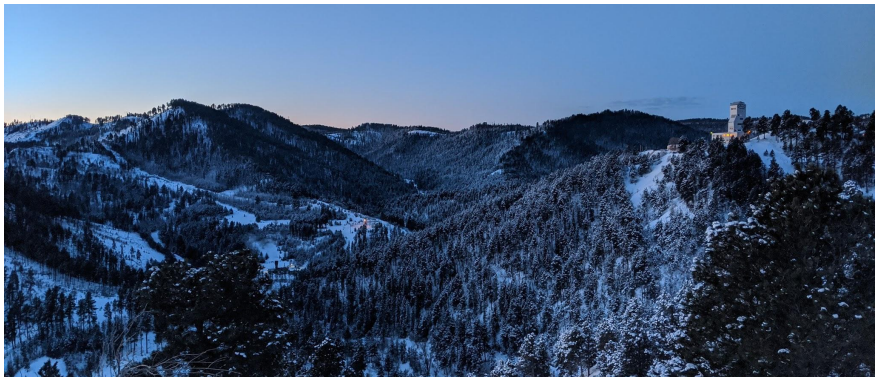
17t Gd-loaded liquid scintillator
+
High purity water



Sanford Underground Research Facility

Homestake Mine in Black Hills of Lead, SD (USA)



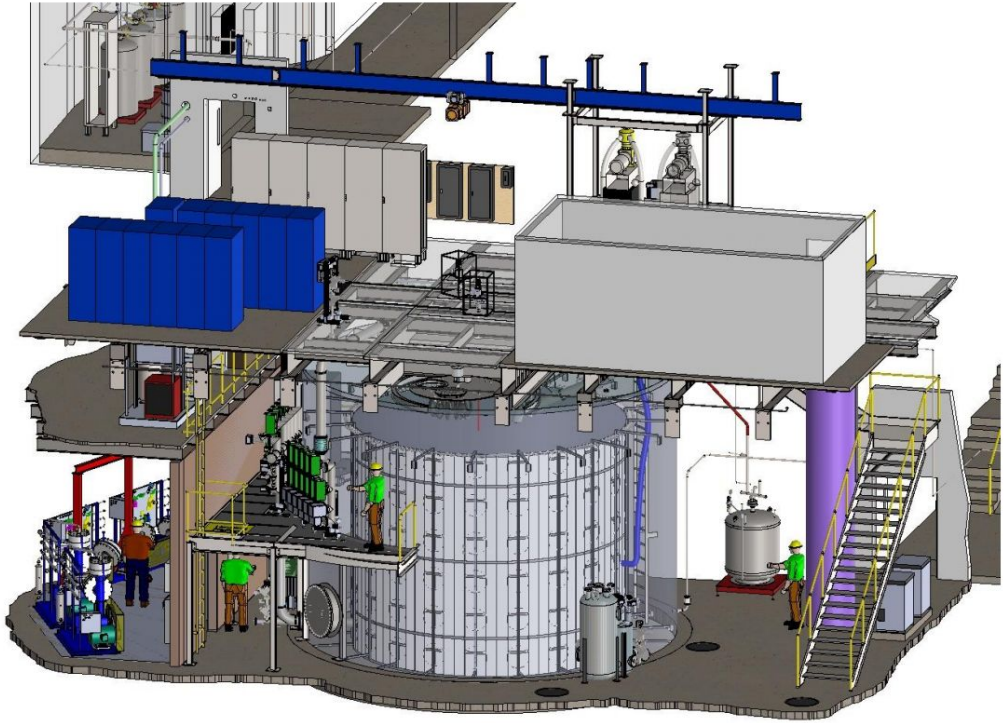


Davis Cavern @ 4850 level

Original home of Davis solar neutrino experiment:

~1.5 km underground, 4300 m.w.e. overburden

Muon flux reduced by O(10^7)

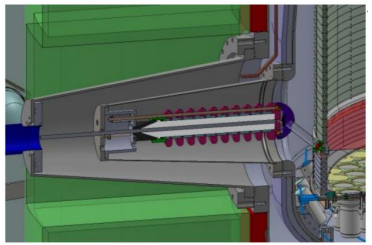


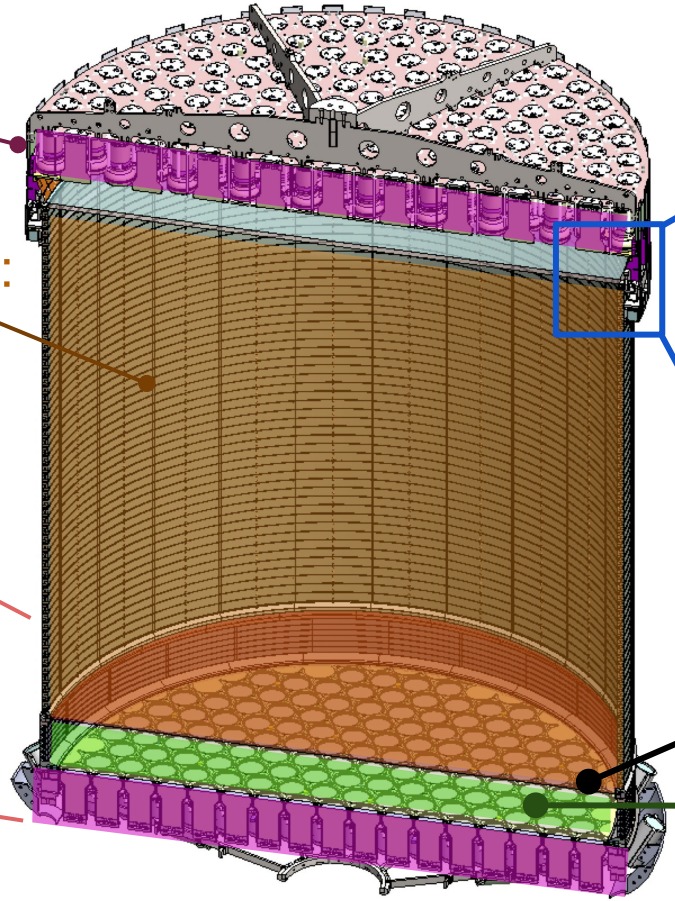
LZ TPC Design

2x PMT arrays
494 PMTs total

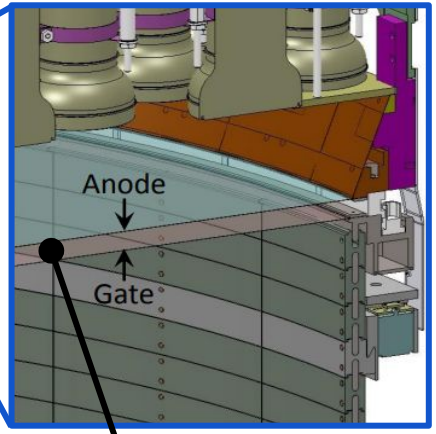
Forward field region:
300V/cm
~1.5 m x ~1.5 m

50kV cathode HV





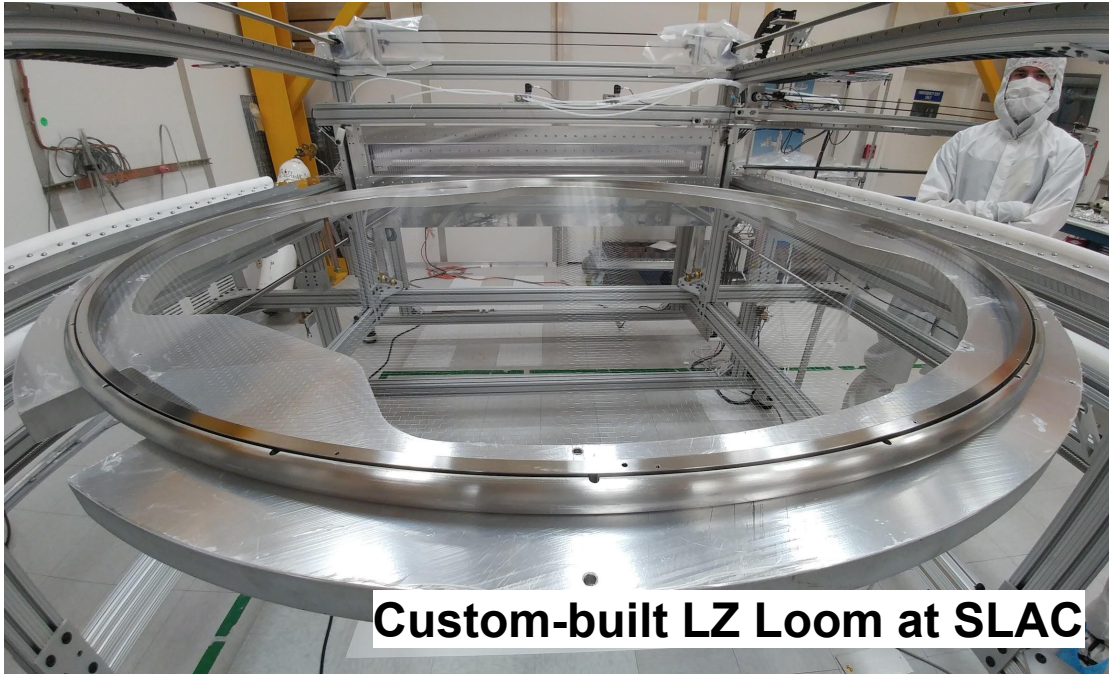
"Extraction Region"
Gas phase and electroluminescence



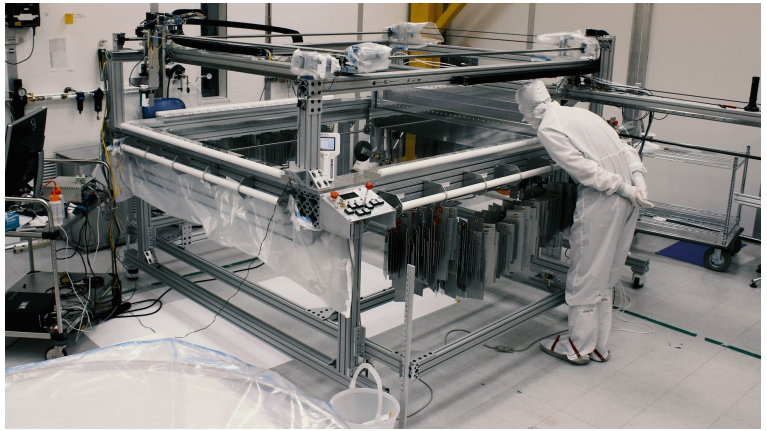
4x wire grid electrodes

Reverse Field Region:
3.5kV/cm

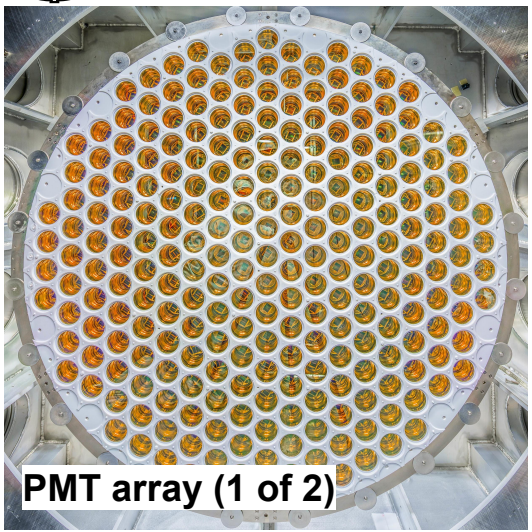
Grid production at SLAC

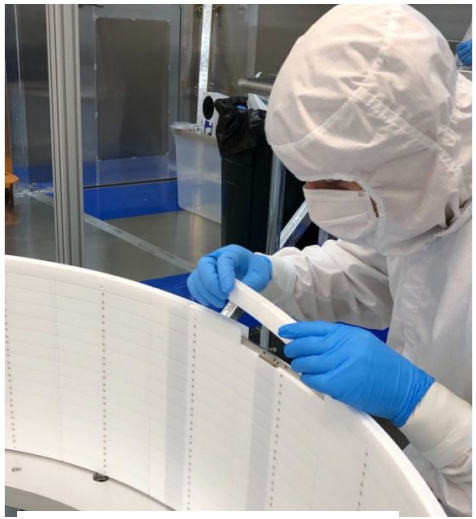

Custom-built LZ Loom at SLAC

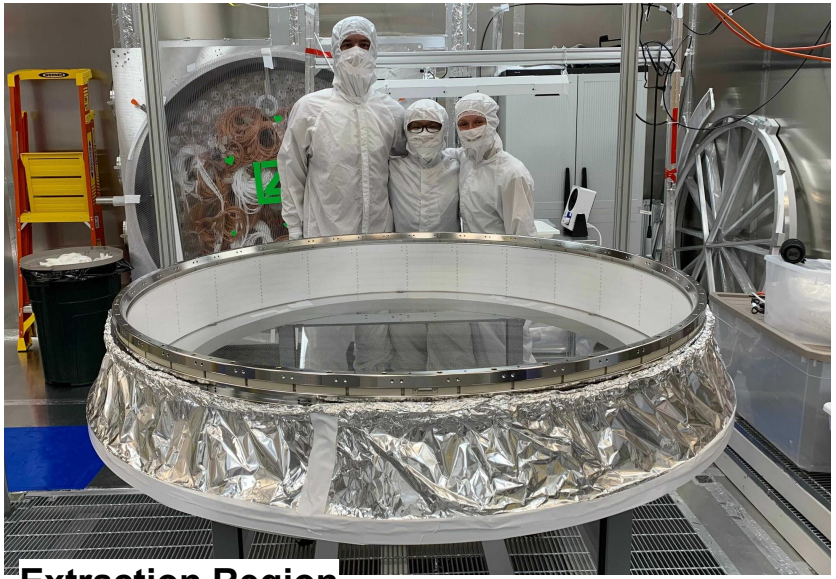

Semi-automated weaving

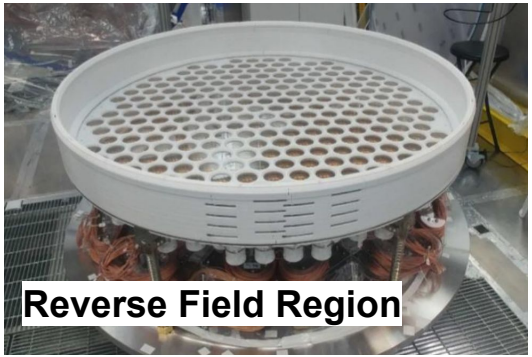


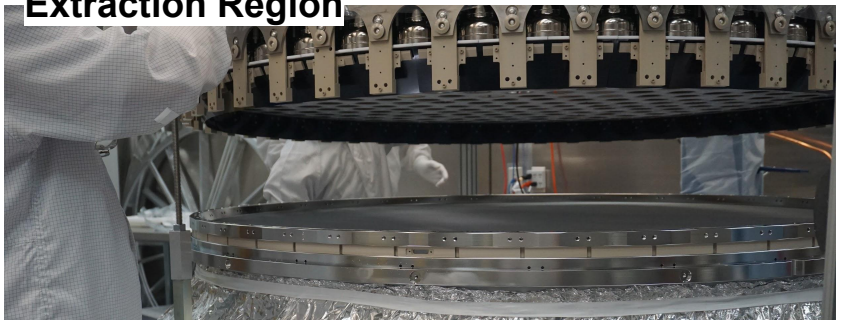
TPC Assembly


PMT array (1 of 2)

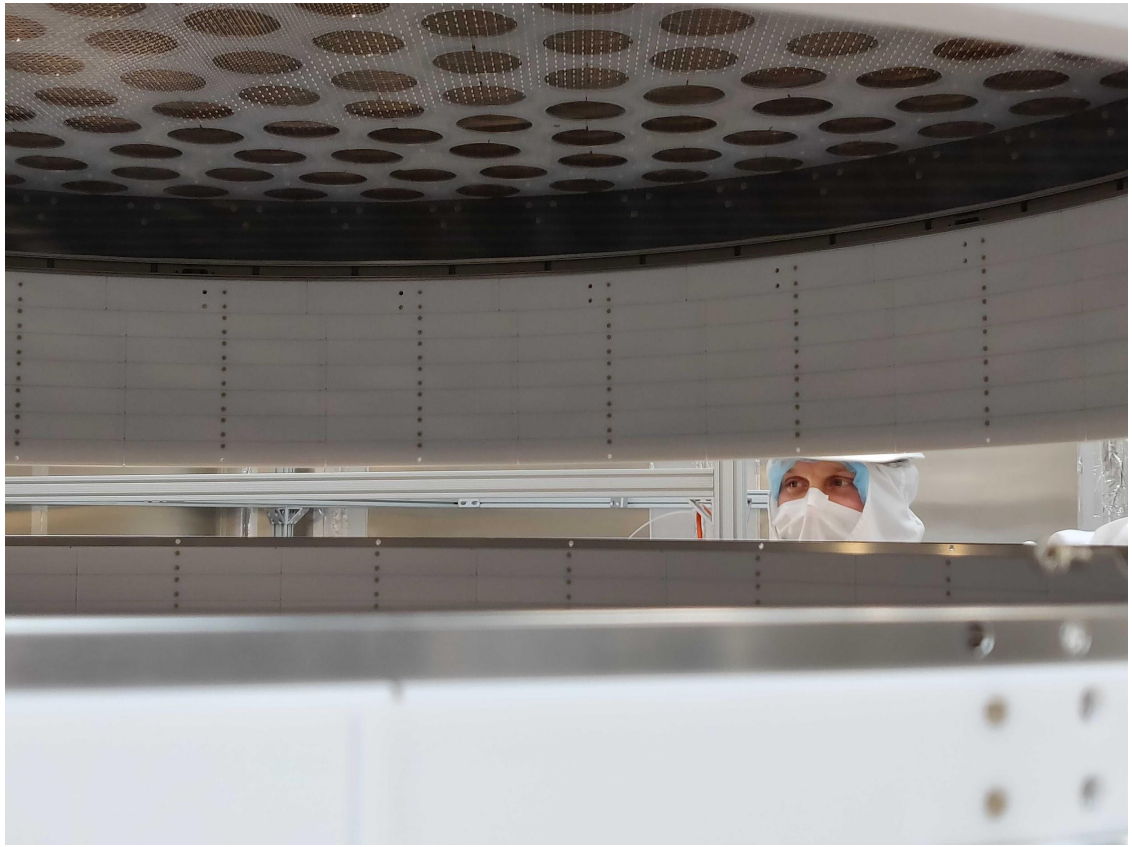

Forward Field Region


Extraction Region


Reverse Field Region

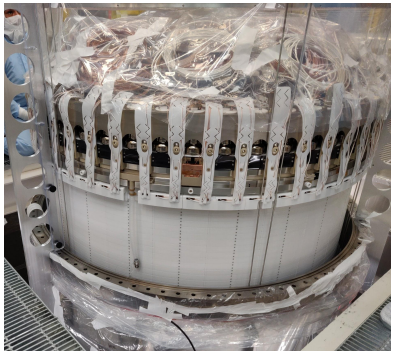


TPC Mating



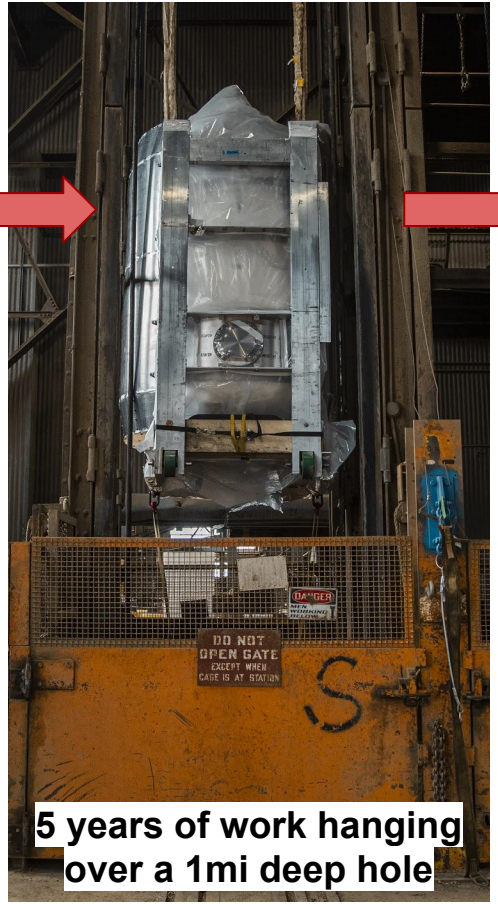
TPC Installation


Full TPC




Ultra-pure titanium vessels

TPC Transportation



5 years of work hanging over a 1mi deep hole

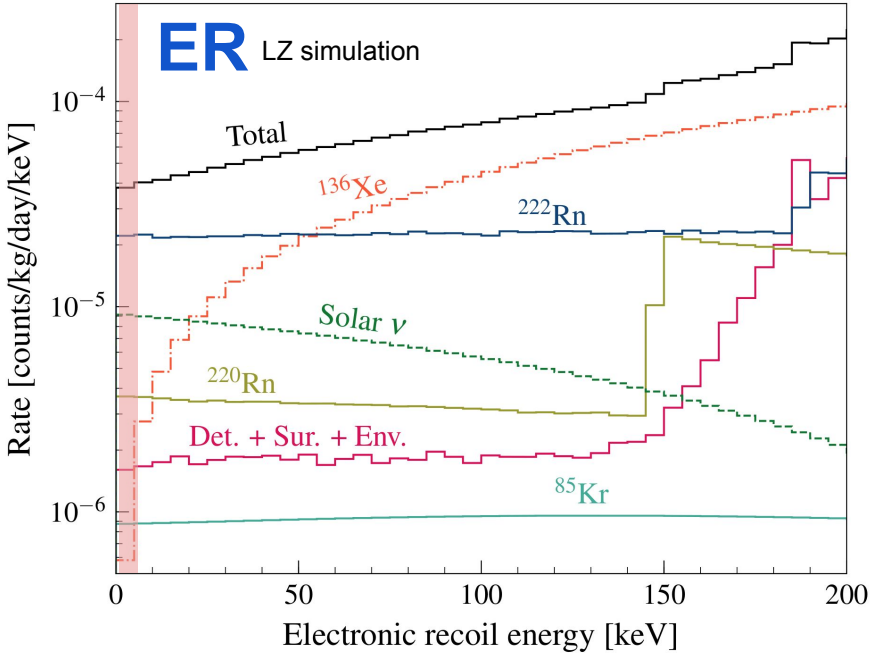
Installed in outer vessel in LZ water tank

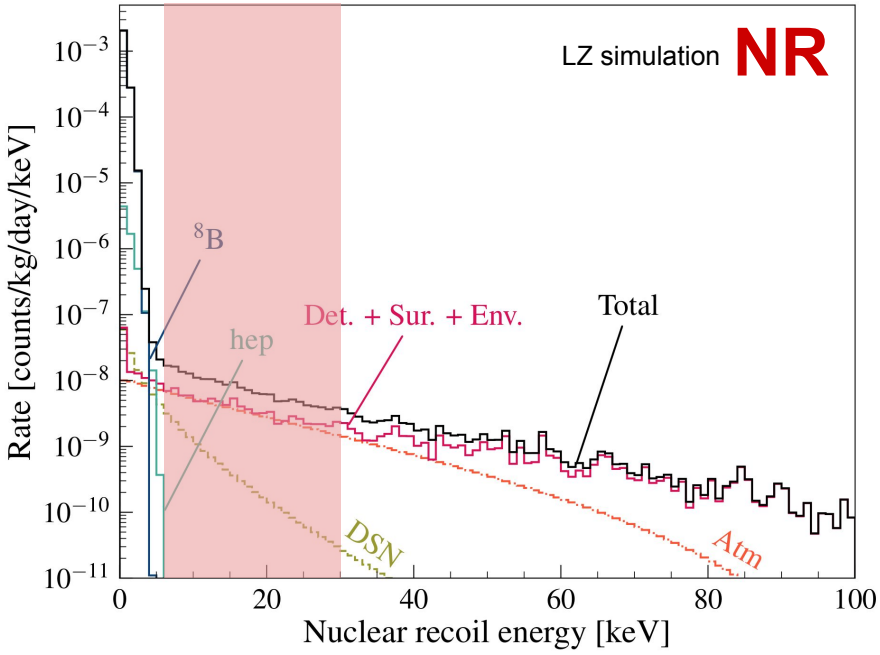
Backgrounds in LZ

1. Overview
2. Mitigation
3. Analysis

Expected backgrounds in LZ

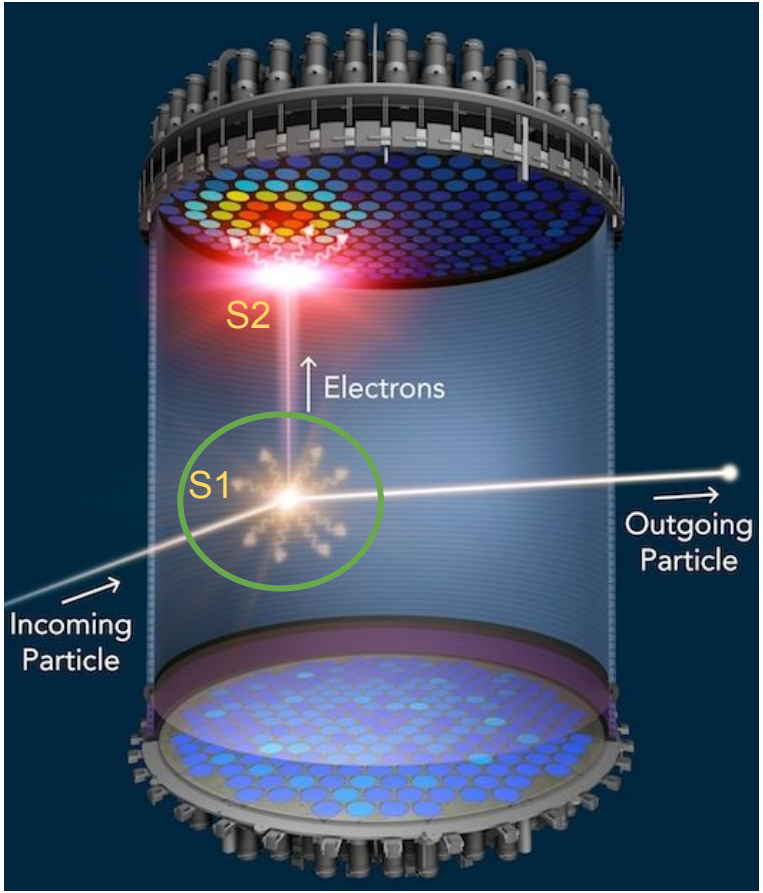
5.6t fiducial (central, radio-quiet) volume, 1000 live-days
single scatters, anti-coincidence with vetoes

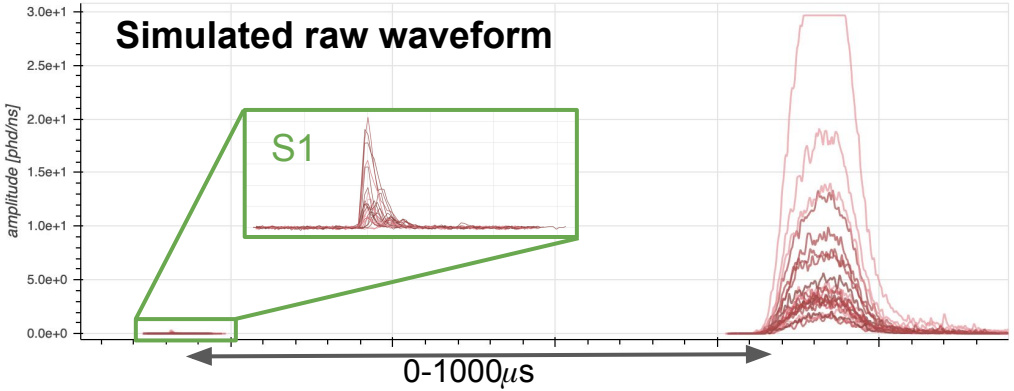




= WIMP search region

TPC waveforms





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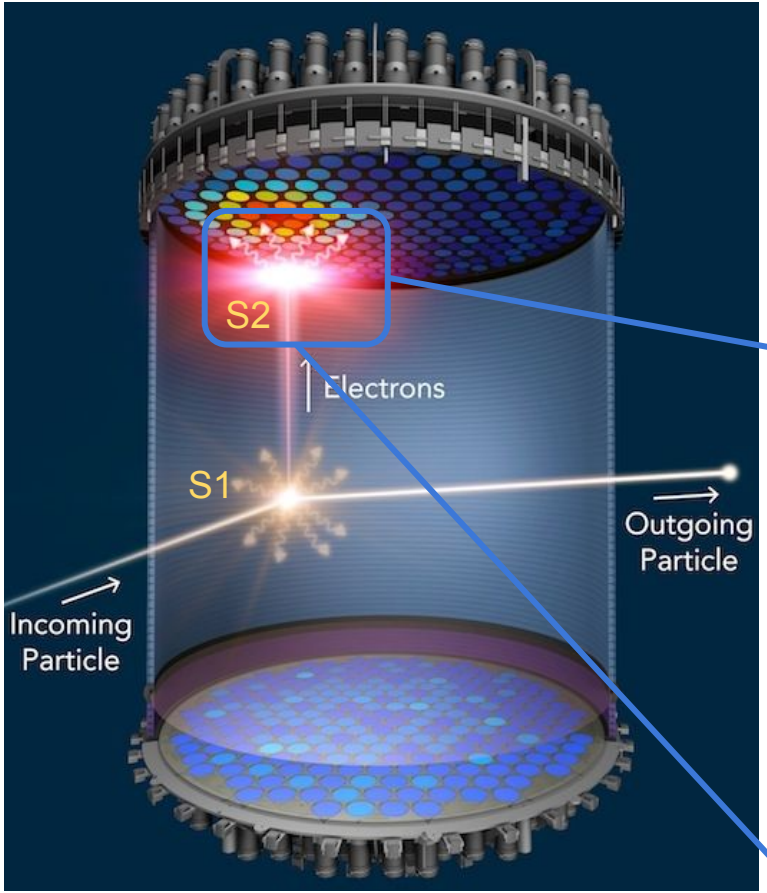
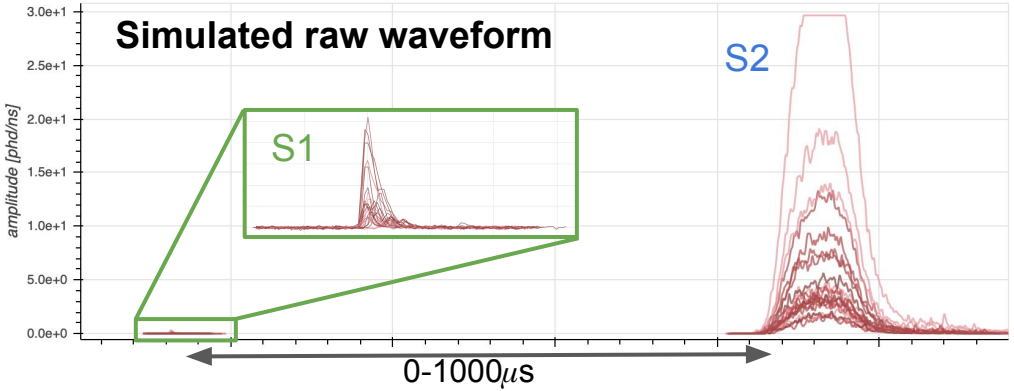
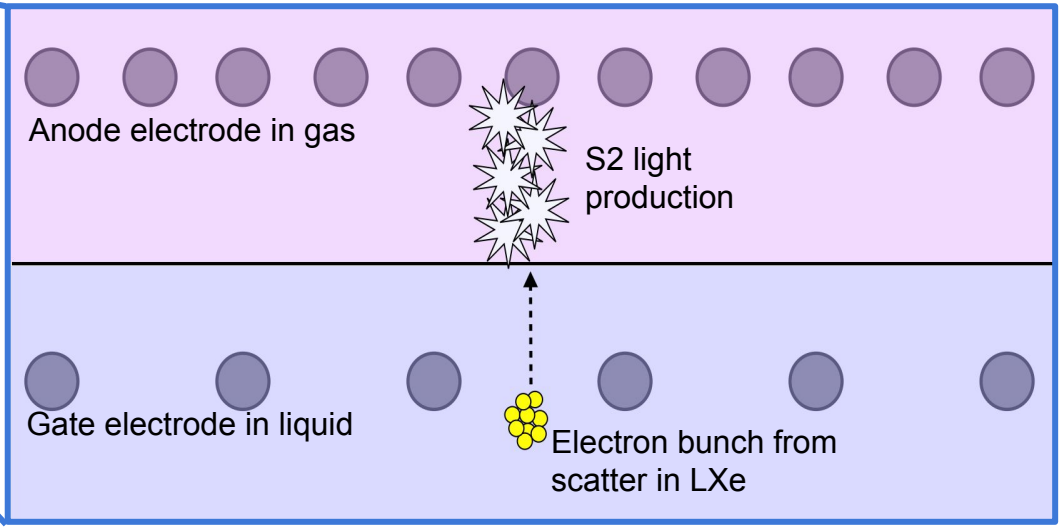
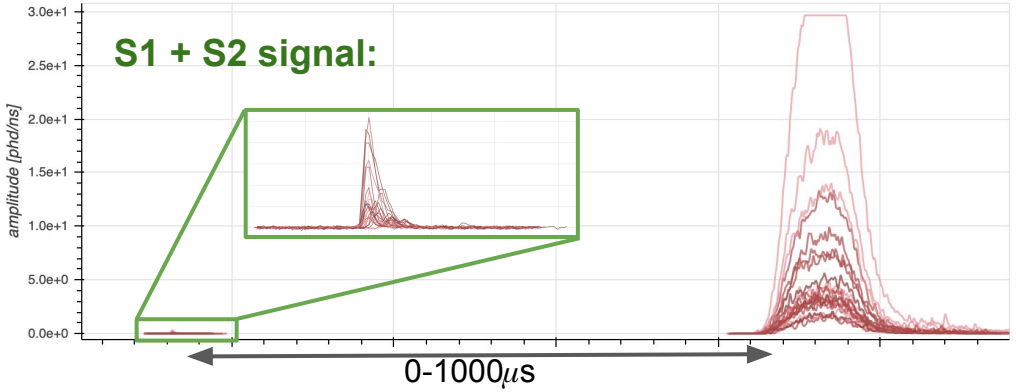




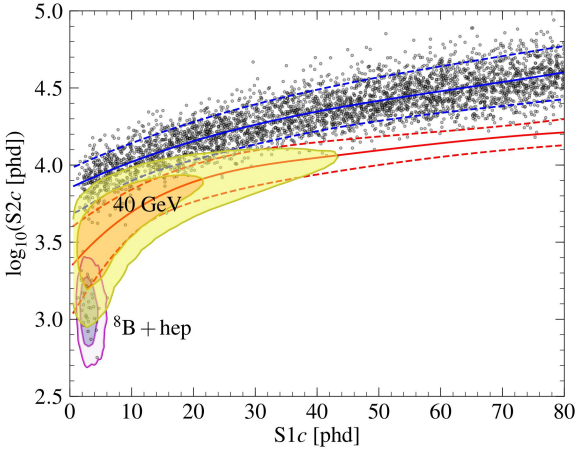


Xenon WIMP searches

LZ Sensitivity arXiv:1802.06039
XENON 1T S2-only results arXiv:1907.11485



Simulation of 1000 days of LZ **S1 + S2** WIMP search



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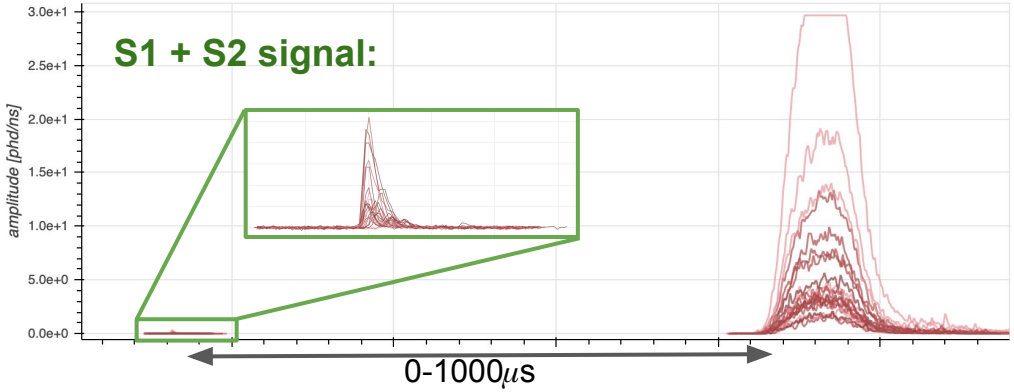
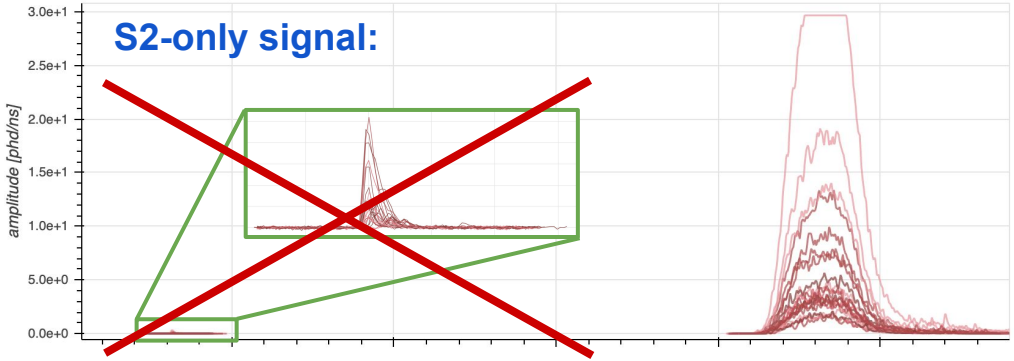
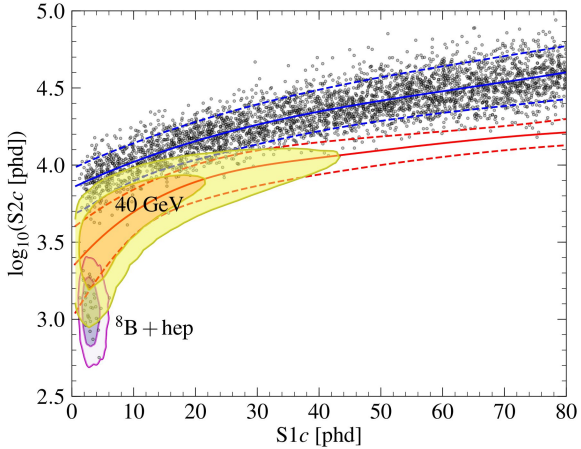
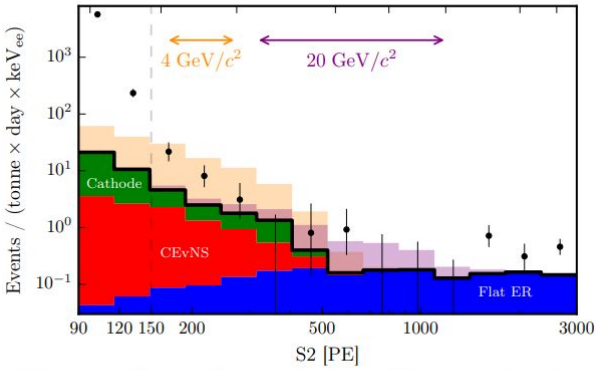




Simulation of 1000 days of LZ **S1 + S2** WIMP search



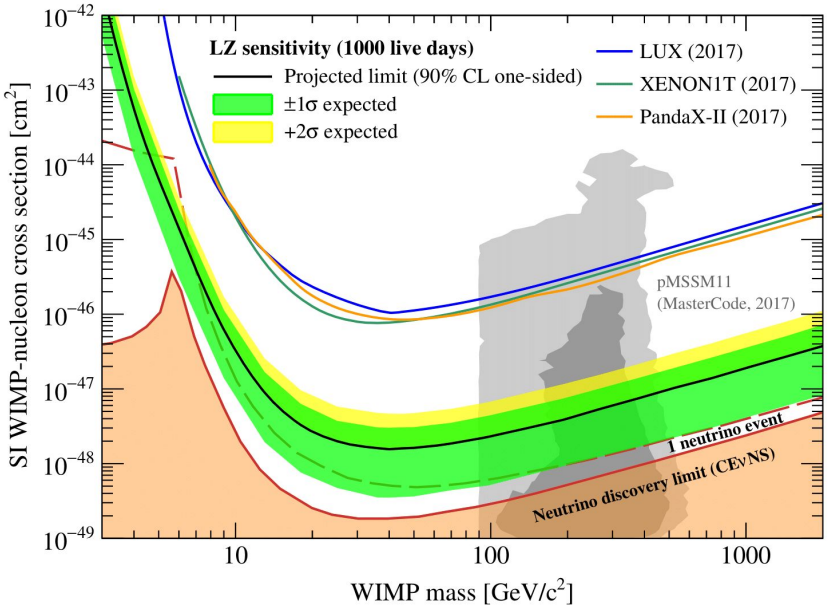
XENON1T results of **S2-only** WIMP search



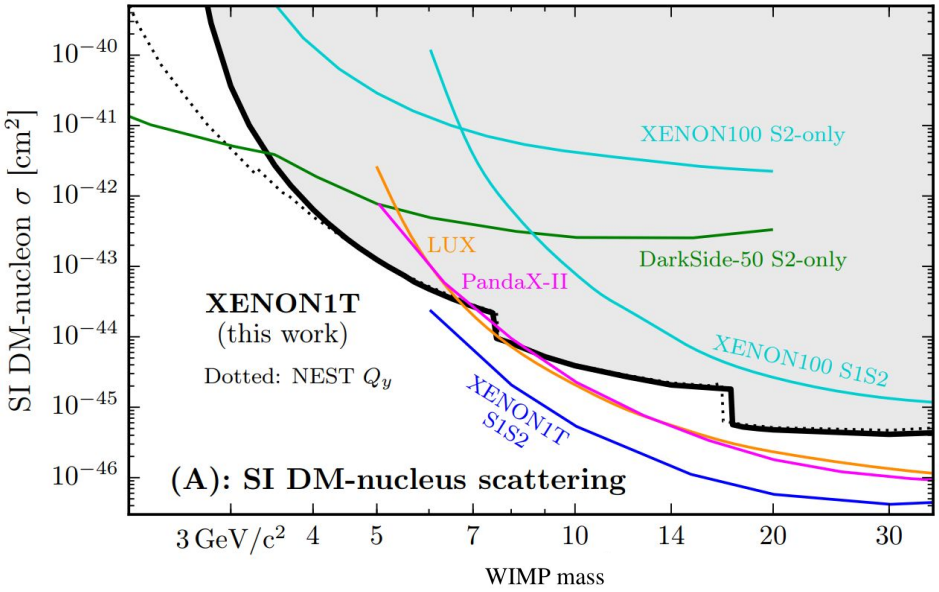
Xenon WIMP searches

LZ Sensitivity arXiv:1802.06039
XENON 1T S2-only results arXiv:1907.11485

LZ S1 + S2 WIMP search projection



XENON1T S2-only WIMP search limit

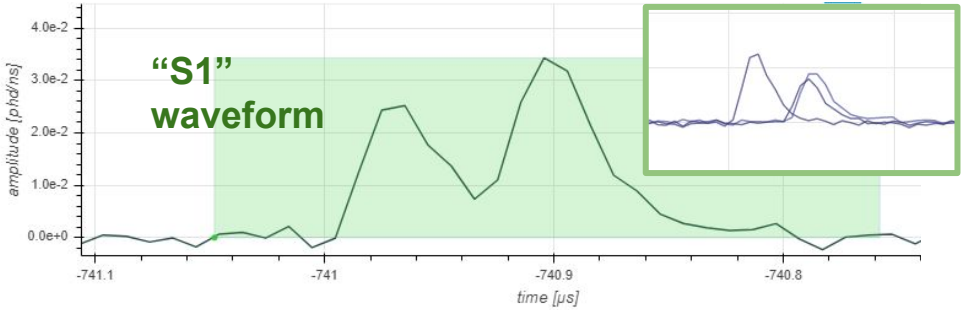


Instrumental backgrounds

Backgrounds arising from pathological detector effects

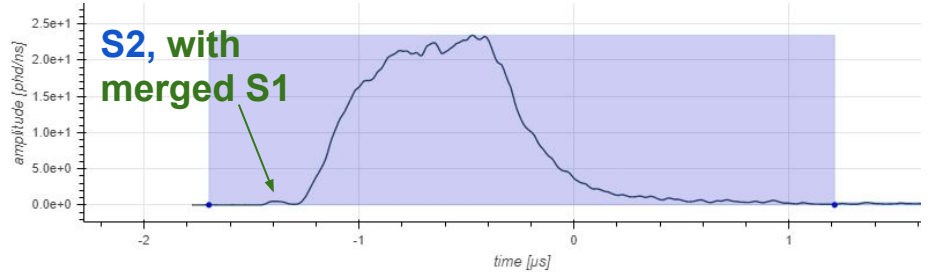
Examples (among many):

If 3+ PMT dark counts pile up within ~150ns, can be mistaken as an S1:



Individual PMT traces

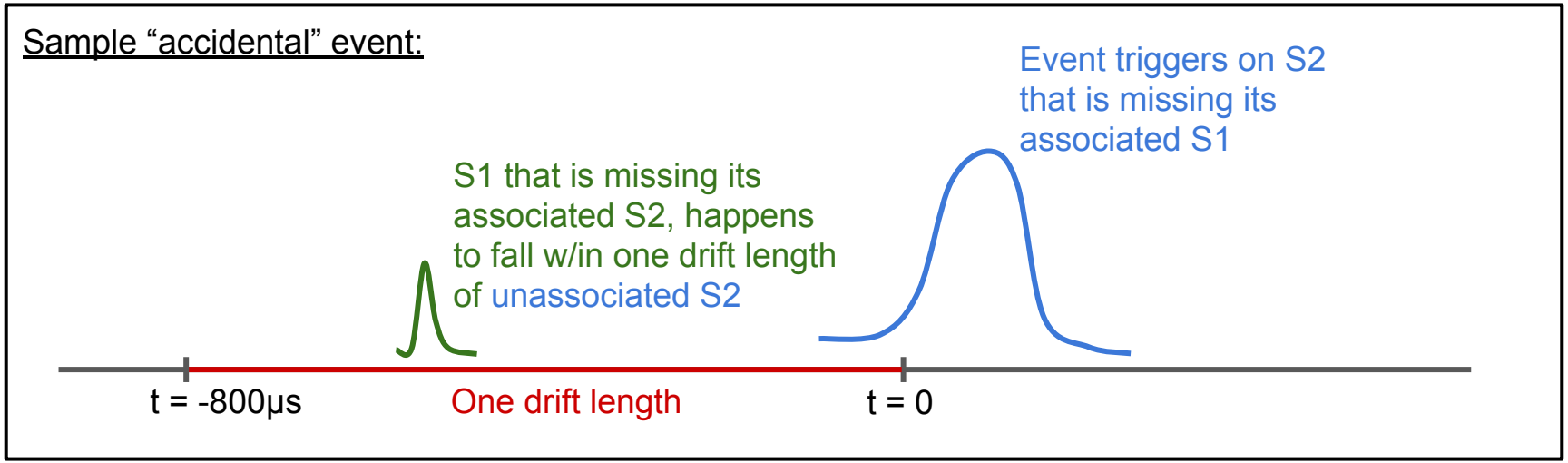
If the drift length of an event is very short, the S1 can become merged with the S2:



Often manifest as S1- or S2-only signals

“Accidental” events

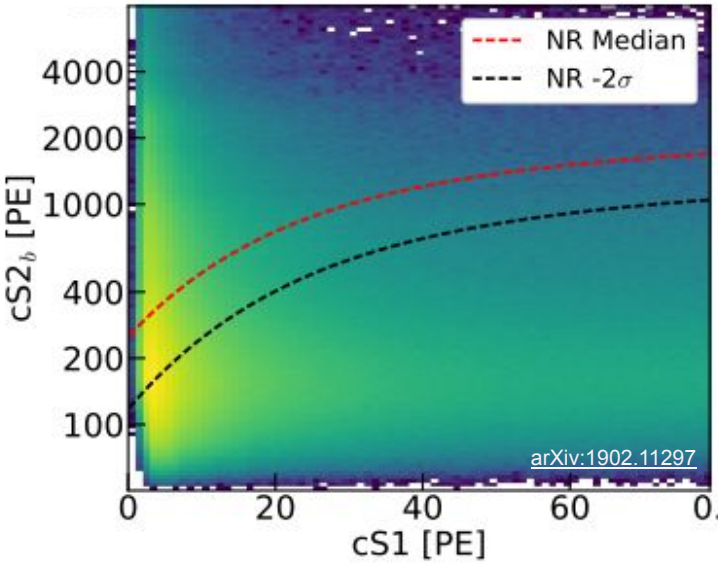
Pile up of uncorrelated S1 and S2 within one drift length



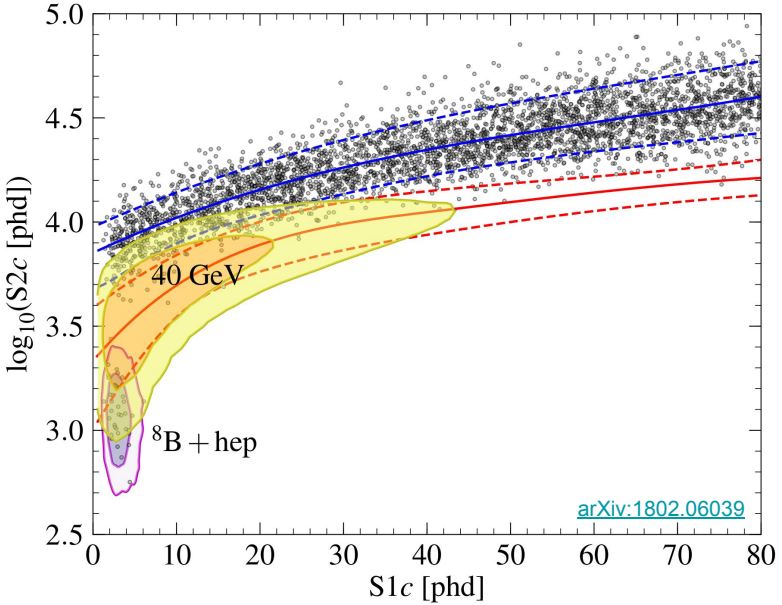
Impact of accidentals on S1 + S2 search

Can look like a low-energy single scatter and appear in nuclear recoil signal region

Accidental model from XENON1T



Simulation of 1000 days of LZ WIMP search

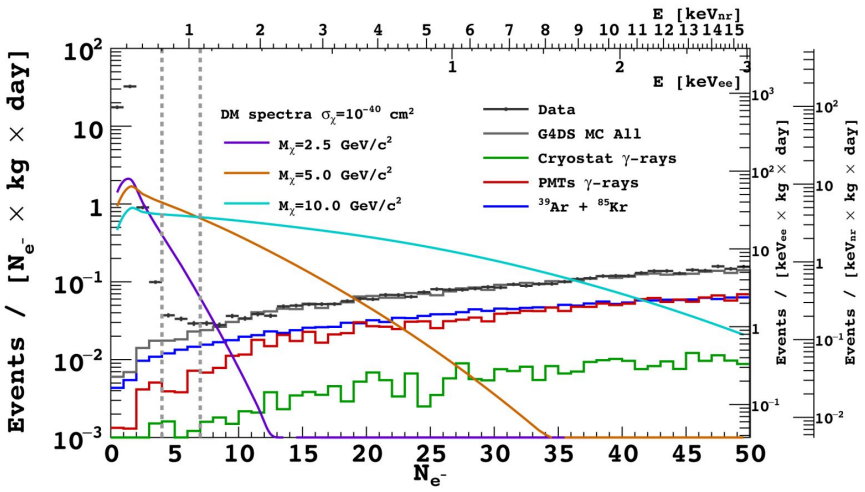


Especially problematic for solar neutrino search, other low energy searches

Instrumental effects in other experiments?

Uncharacterized S2 excesses seen at low energies

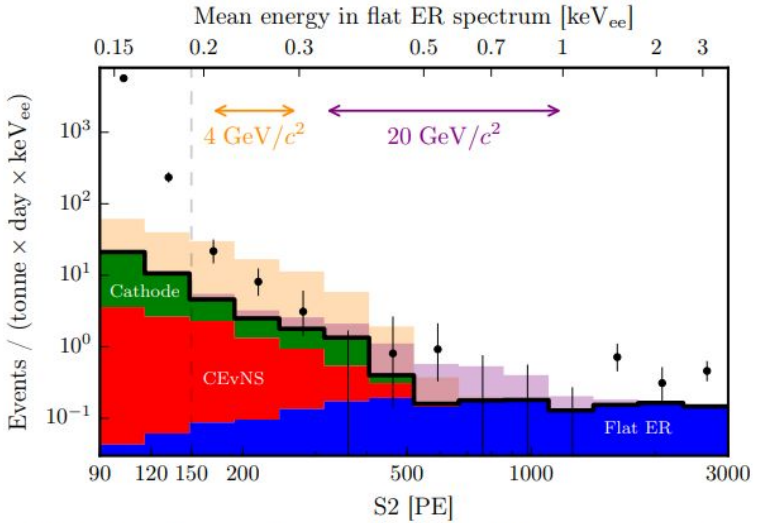
DarkSide-50 S2-only search results



There is an excess of data in the region of N_{e^-} of $4\,e^-$ to $7\,e^-$, the origin of which is left for future study.

DarkSide-50 S2-only results arXiv:1802.06994

XENON1T S2-only search results



Below 150 PE, the rate rises quickly, likely due to unmodeled backgrounds.

XENON 1T S2-only results arXiv:1907.11485

Instrumental effects in LZ

Very challenging

- Hard to predict all sources
- For predicted sources, hard to predict rate + spectrum
- Difficult to remove through traditional analysis techniques

Becoming increasingly important

- Many instrumental backgrounds irreducible, scale with detector size
- Other backgrounds being reduced through material selection, handling, etc.

What is being done in LZ?

1. Predict sources of instrumental backgrounds
2. If possible, mitigate sources through careful design and treatment
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Predicted S1-only sources in LZ

PMT dark count pile up

Gas events

Light leaks from outside TPC

Radioactivity from anode wires

Cherenkov: PMT windows, PTFE walls

Fluorescence of PTFE walls

Events near TPC walls

RFR events

Scales with circumference
Scales with diametric area
Scales with vertical area

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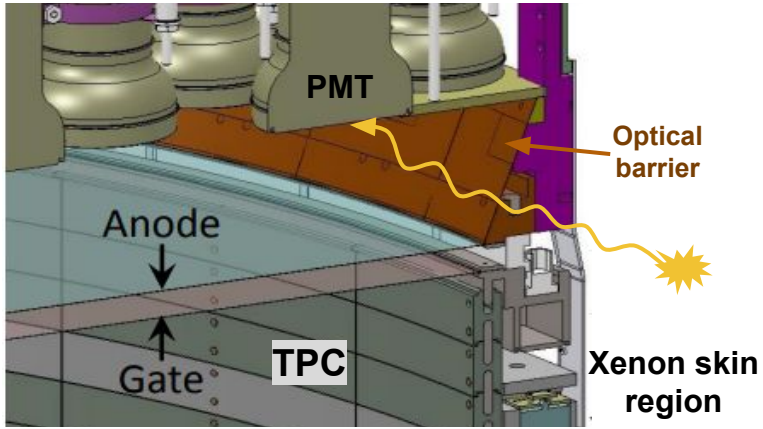
Events near TPC walls

RFR events

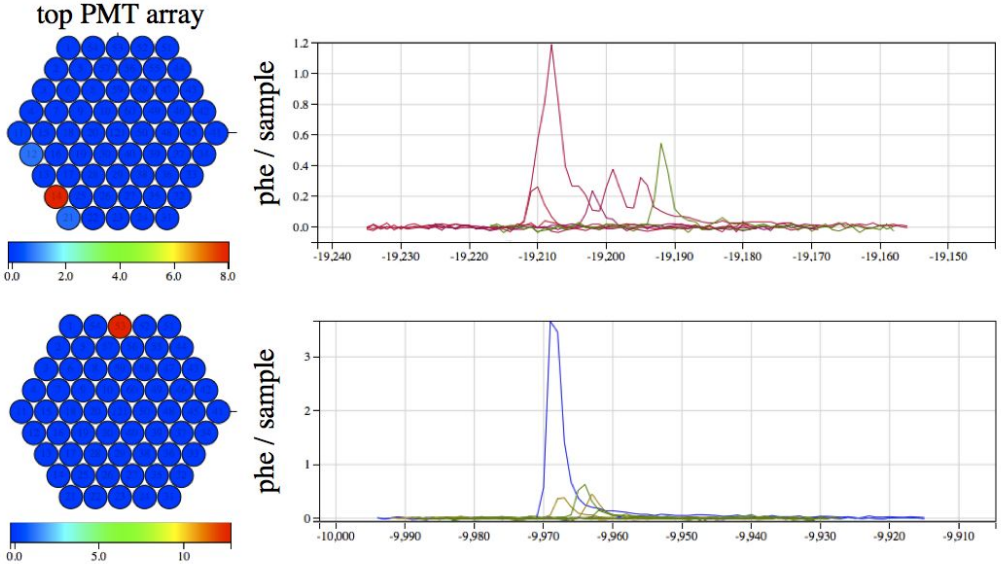
Scales with circumference
Scales with diametric area
Scales with vertical area

S1-only source: Light leaks

Scintillation light from the xenon skin region can leak into TPC through extraction region, look like **S1 pulse**



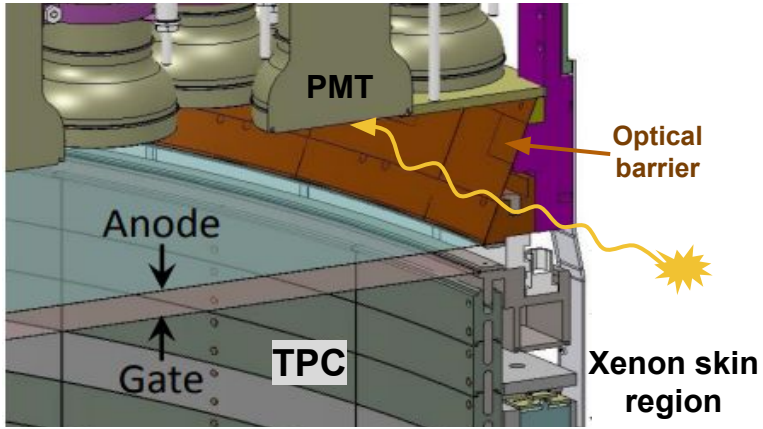
Seen in LUX:



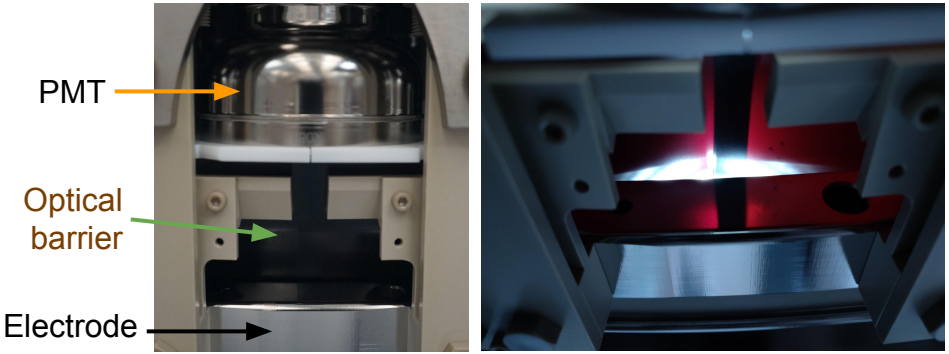
Characteristics:

- Single PMT
- Near edge

Mitigation:
Improved light baffles in LZ

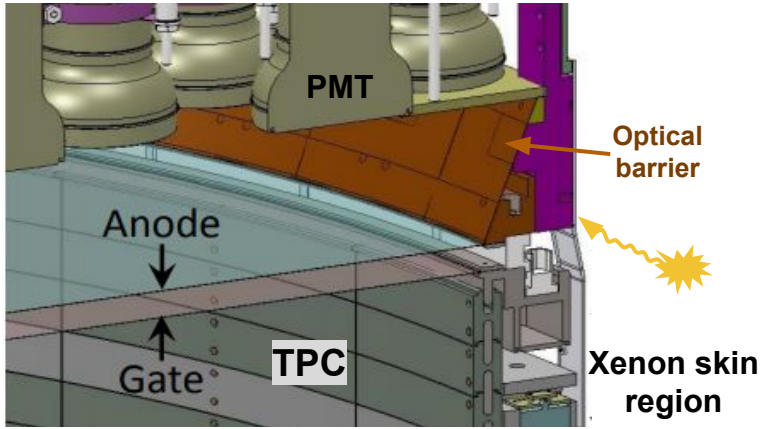


Cracks seen in LZ optical barrier:

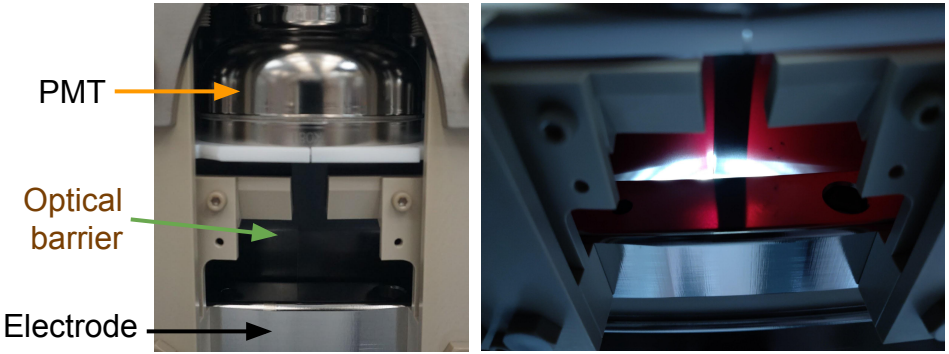


Looking into the extraction region from the xenon skin

Mitigation: Improved light baffles in LZ



Cracks seen in LZ optical barrier:

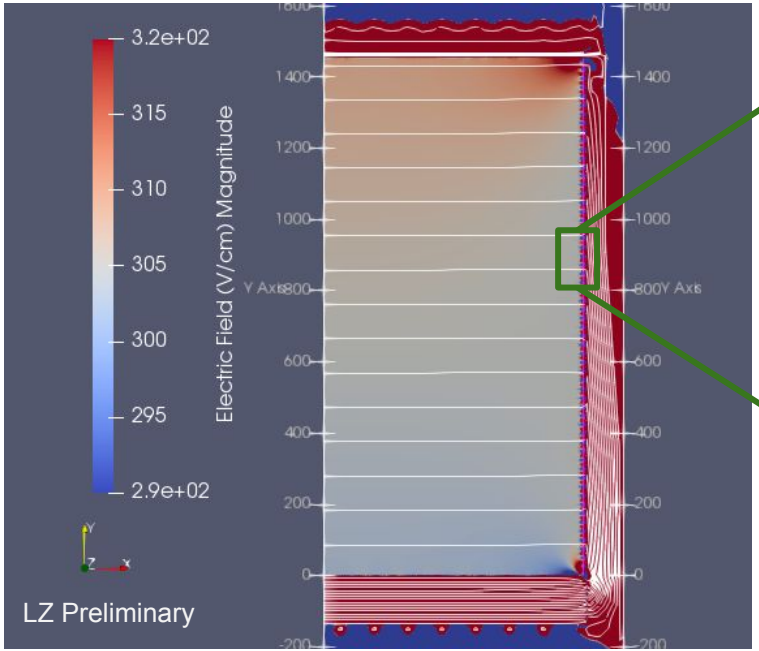


Looking into the extraction region from the xenon skin

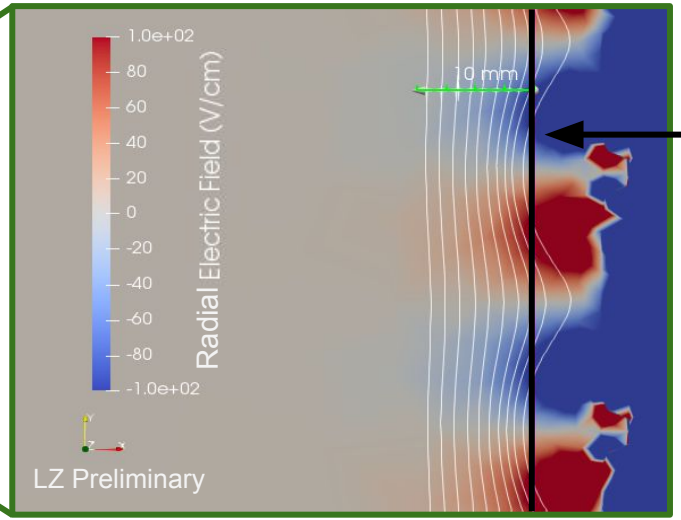
Improved light baffles:

Credit: R. Watson

S1-only source: Charge loss near walls



Uniform LZ E-field: optimized electrode voltages + field cage resistors



Non-uniformities along walls lead to "S2-dead" regions where electrons attach to wall → creates S1-only events

Predicted S2-only sources in LZ

Gas events

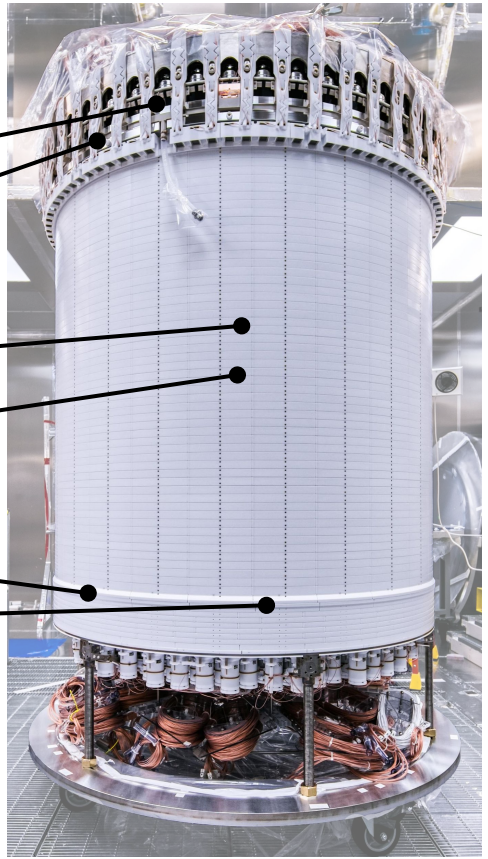
Events at liquid-gas interface

Sub-S1 threshold ER events

Electrons in S2 tails

Radon daughters from cathode/gate

Electron emission from grids



Scales with volume

Scales with diametric area

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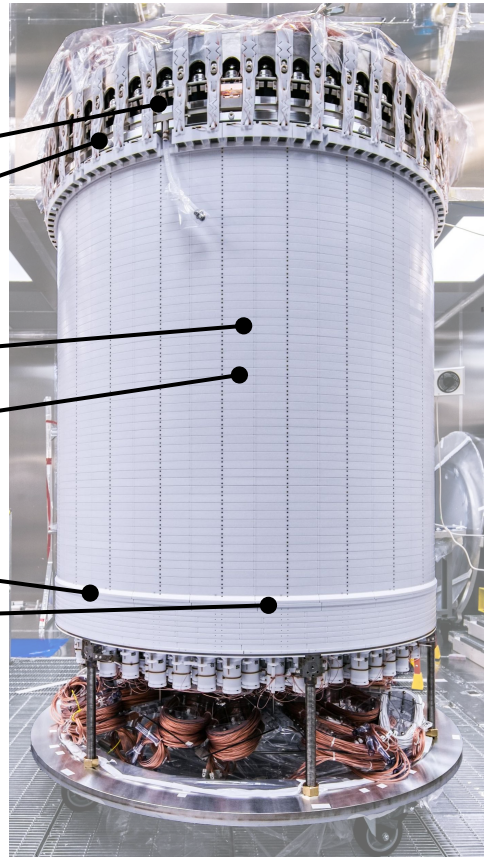
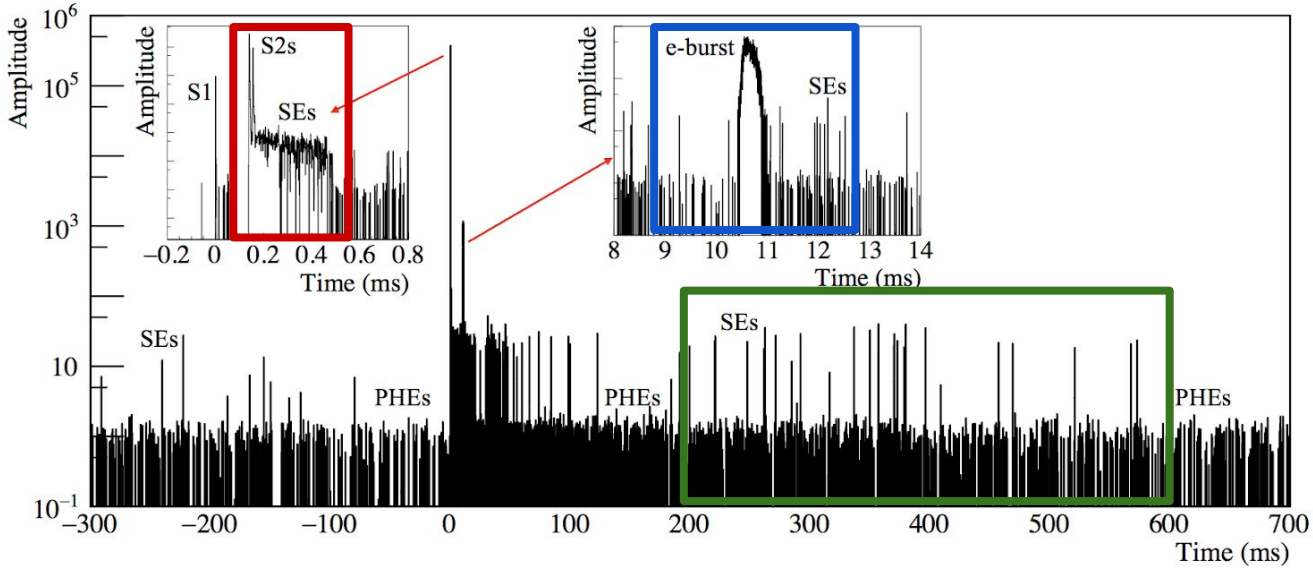


Scales with volume

Scales with diametric area

S2-only source: Electrons following S2s

Electron backgrounds at several time scales seen in LUX data:



Possible explanations:

Prompt electrons: photoionization of impurities

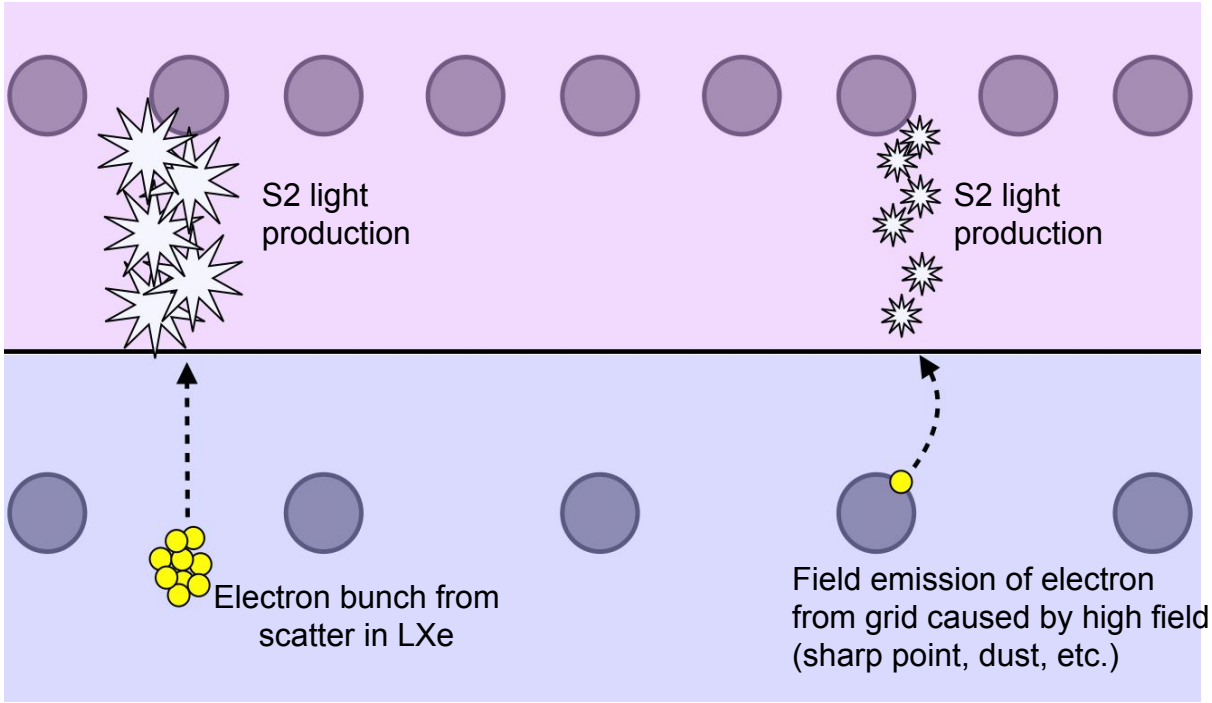
"E-bursts": electrons trapped at liquid surface

Delayed electrons: ionization of electrons captured by impurities?

Mitigations: high purity, high extraction voltage, implementation of "hold-off" time after event in LZ analysis

LUX electron emission arXiv:2004.07791

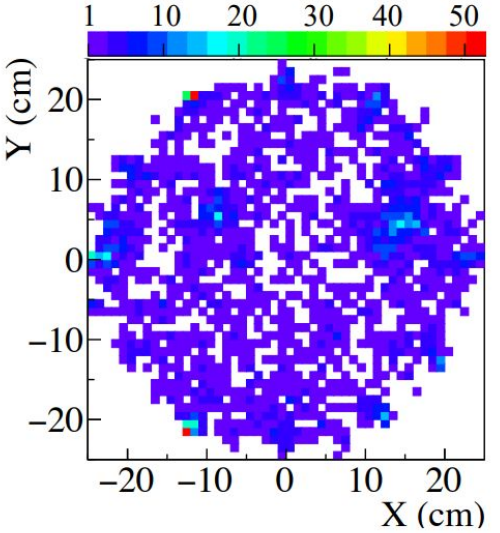
S2-only source: Electron Emission from HV electrodes



LUX extraction voltage limited by emission from grids

Gain processes seen in LUX, 2+ electrons **(right)**

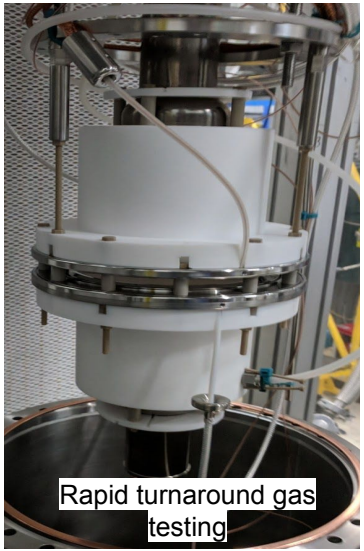
Position of 2.5+ e- events

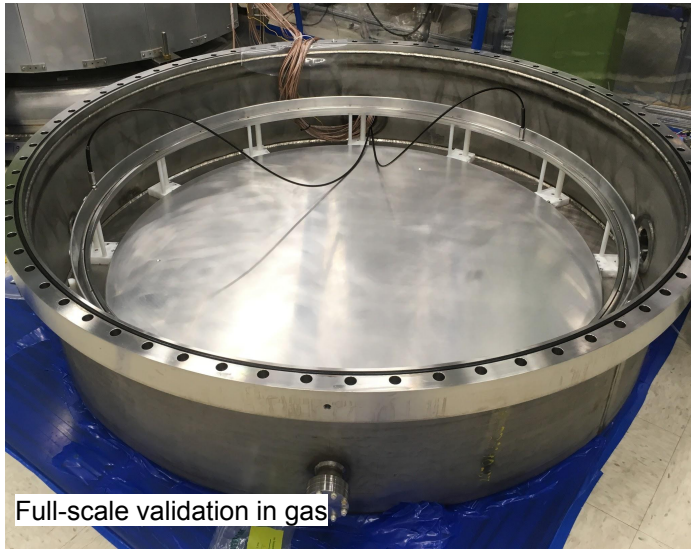


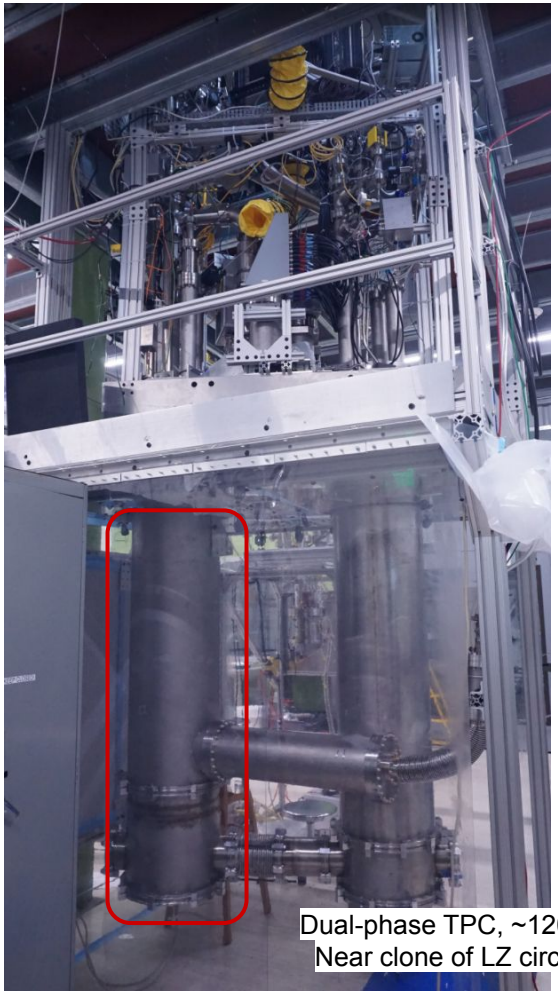
LUX electron emission arXiv:2004.07791

Mitigation: Grid testing

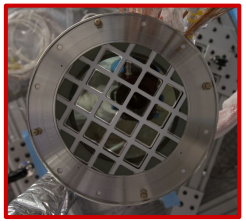
Suite of three detectors built at SLAC to enable comprehensive testing of critical LZ systems: xenon circulation, extraction region, high voltage electrode performance


Rapid turnaround gas testing

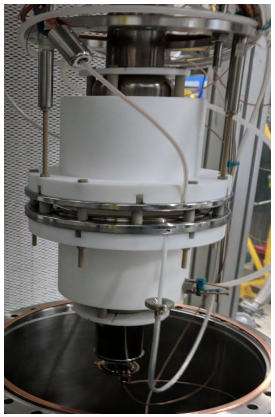

Full-scale validation in gas

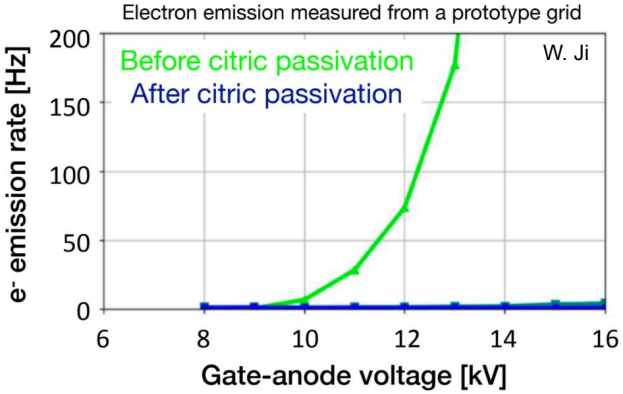

Dual-phase TPC, ~120kg LXe
Near clone of LZ circulation

32 1” PMTs

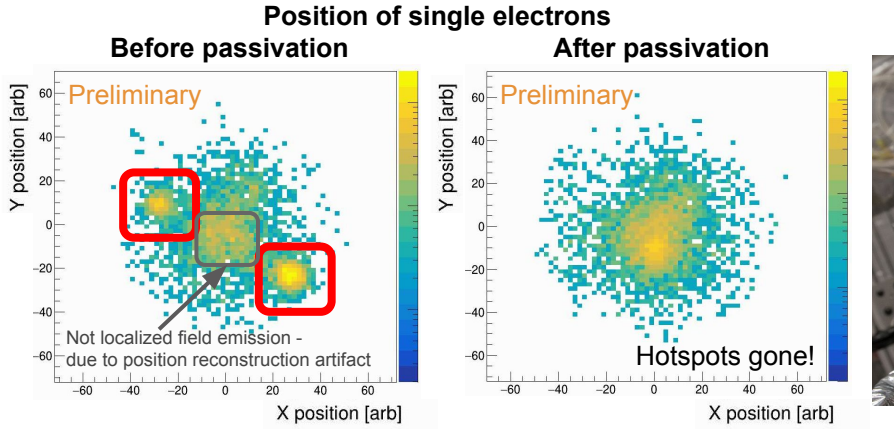


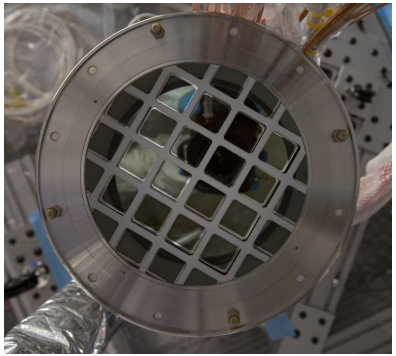
Mitigation: Grid treatment





Results from two detectors show significant reduction in electron emission (overall rate and localized hotspots) after citric acid passivation





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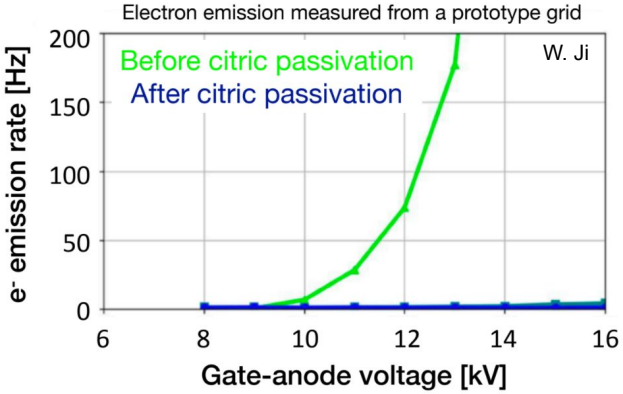

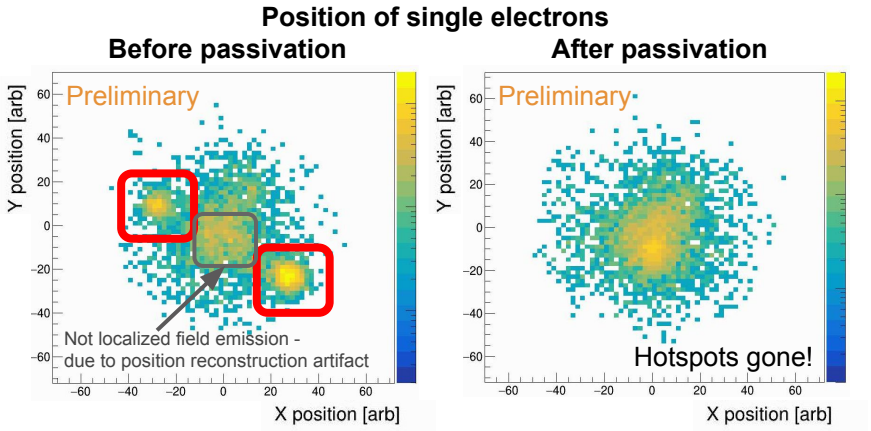

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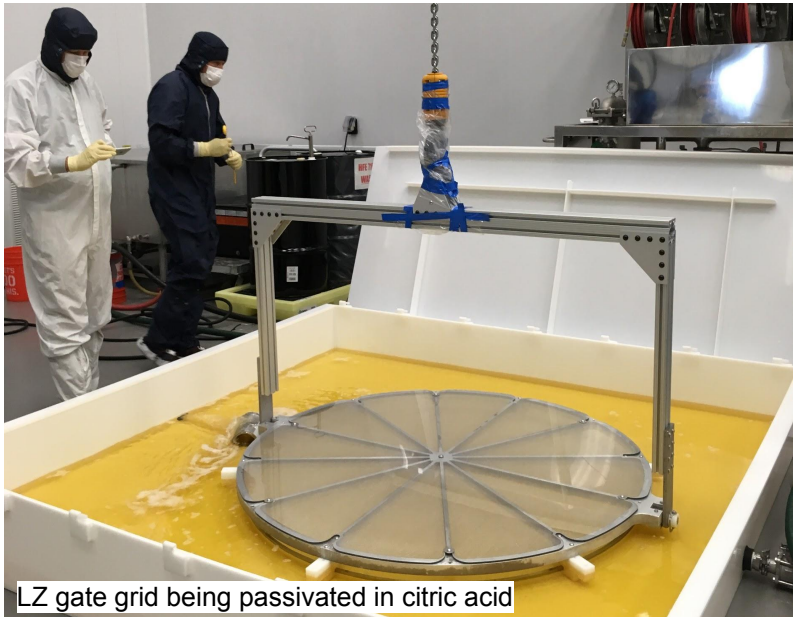
LZ gate grid being passivated in citric acid

Instrumental effects in LZ

What is being done?

1. Predict sources of instrumental backgrounds
2. If possible, mitigate sources through careful design and treatment
3. If can’t mitigate, account through analysis

Instrumental effects in LZ

What is being done?

1. ~~Predict sources of instrumental backgrounds~~
2. ~~If possible, mitigate sources through careful design and treatment~~
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Instrumental effects in LZ

What is being done?

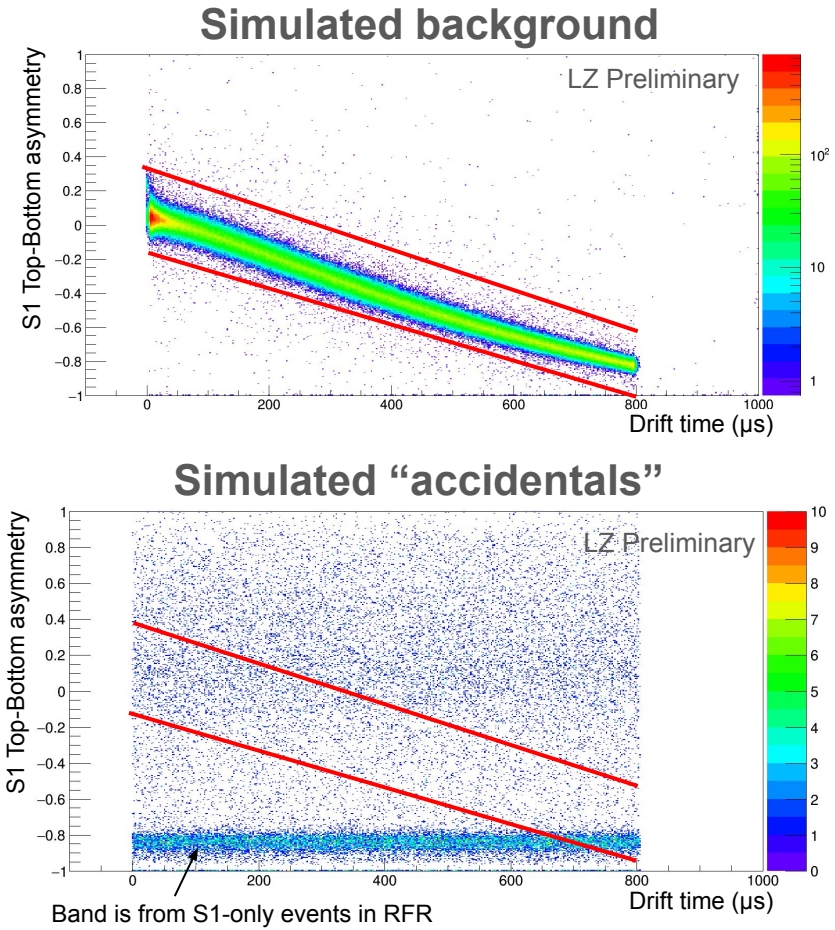
1. ~~Predict sources of instrumental backgrounds~~
2. ~~If possible, mitigate sources through careful design and treatment~~
3. **If can't mitigate, account through analysis**
    a. Remove what you can
    b. Model what you can't

Removing accidentals

Some properties of events are correlated with drift time → can be used to tag accidentals (randomized drift time)

Example **(right)**: hit pattern of S1 light is correlated with drift time in real events, but not in accidentals

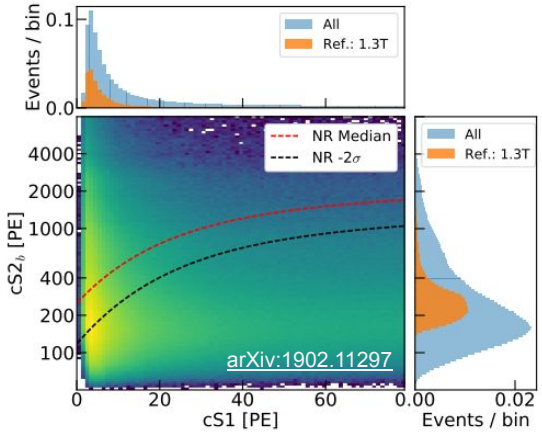
Multivariate likelihood-based approach: in place of simple cuts, combining multiple event properties



Accidentals background model

Data-driven:

XENON1T accidentals model



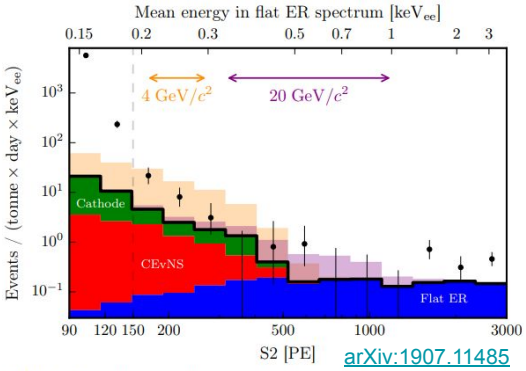
"Simply" get spectra of S1- and S2-only events straight from data, combine into background PDF (above)

Challenges:

- Rate measurement
- Data selection, reconstruction efficiency
- Breaks down if S1- and S2-only sources are correlated

"Bottom-up":

XENON1T S2-only model



arXiv:1907.11485

Understand sources of S1- and S2-only events, combine into background PDF (above, for S2-only)

For each source, need to:

1. Understand physics of mechanism
2. Compute the rate
3. Predict the spectrum

Challenges:

- Very difficult to predict without data
- "Surprises" when we turn on detector

Extension to machine learning techniques

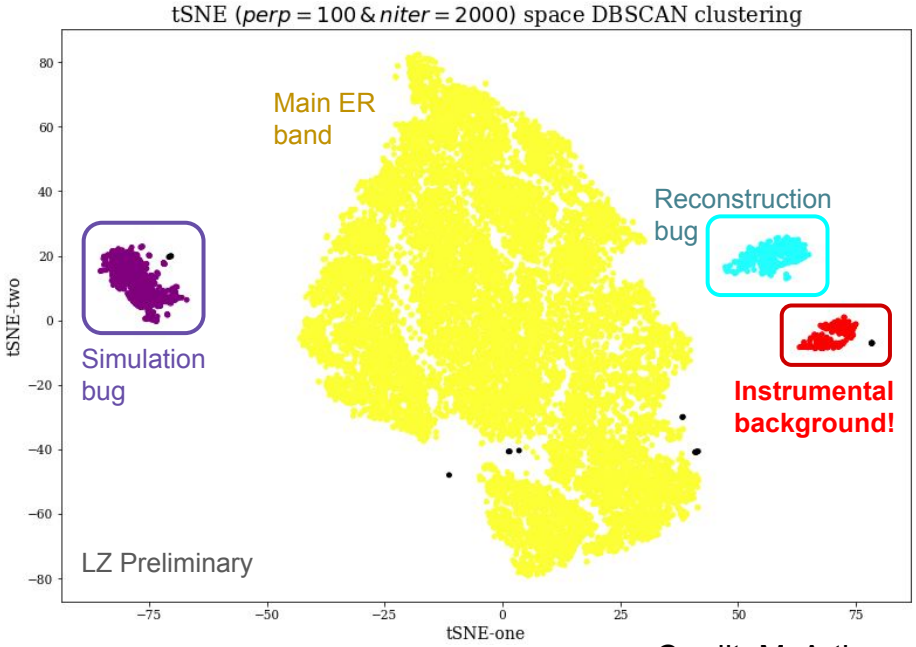
Variety of techniques being explored

Using reconstructed physics quantities:

- Isolation Forest: outlier detection
- T-distributed Stochastic Neighbor Embedding (tSNE): unsupervised clustering, successfully picked instrumental backgrounds **(right)**

Using raw waveforms:

- Recurrent Neural Networks (RNNs)
- Long Short-Term Memory (LSTM) + Fully Convolutional Network (FCN)



Credit: M. Arthurs

Summary

Instrumental backgrounds are:

- Becoming increasingly important as TPCs get larger
- Impactful in low energy physics searches like the main WIMP search and S2-only
- Challenging to model *a priori*

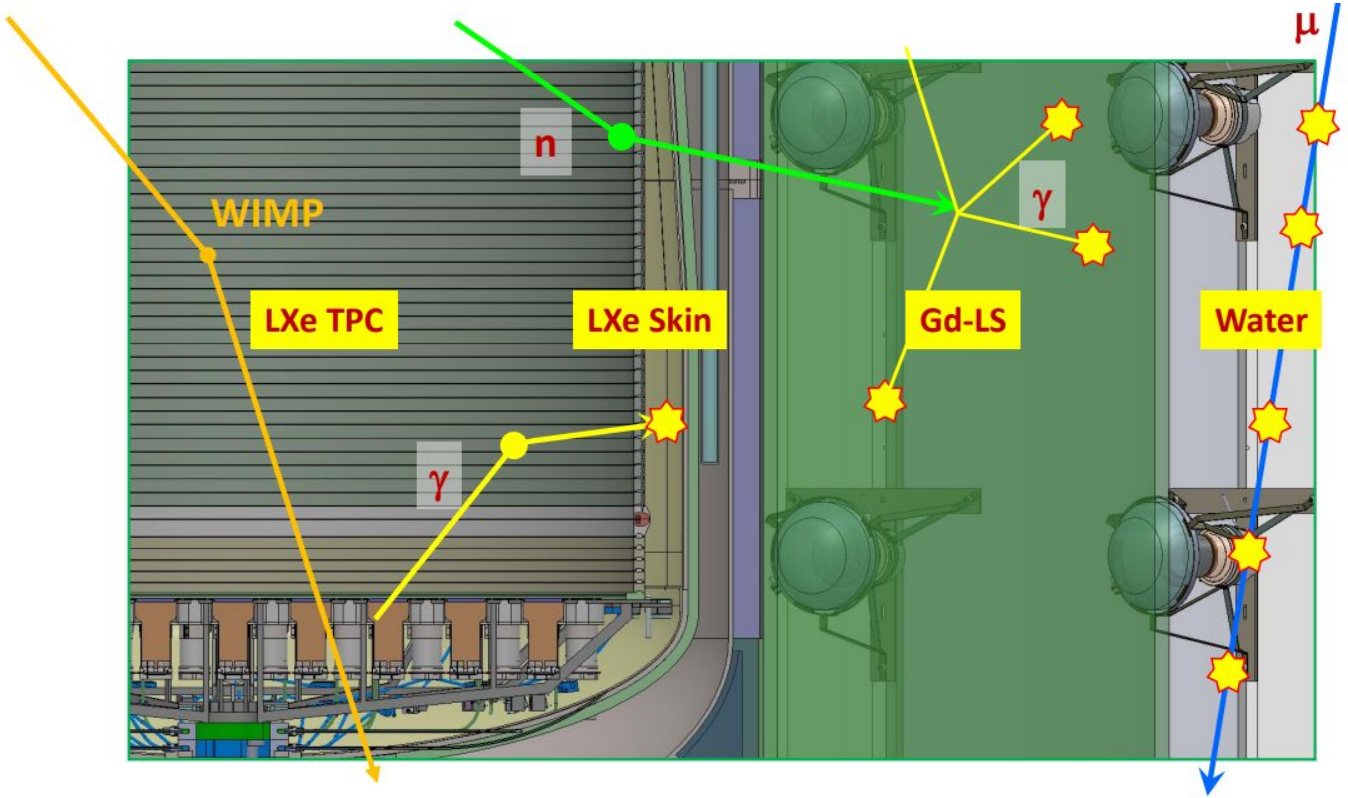
Instrumental backgrounds in the LZ experiment:

- Have been reduced to the extent possible through several innovative techniques
- Are currently being modeled, and will be accounted for in our physics searches

LZ looks forward to taking data in 2021!

Backup

Outer Detector Veto System



- Tag individual neutrons and γ-rays
- Characterize backgrounds in situ

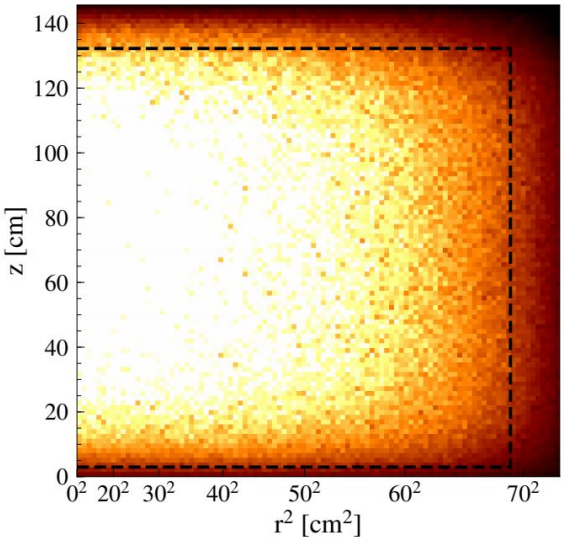
→ Enables discovery potential

Background suppression

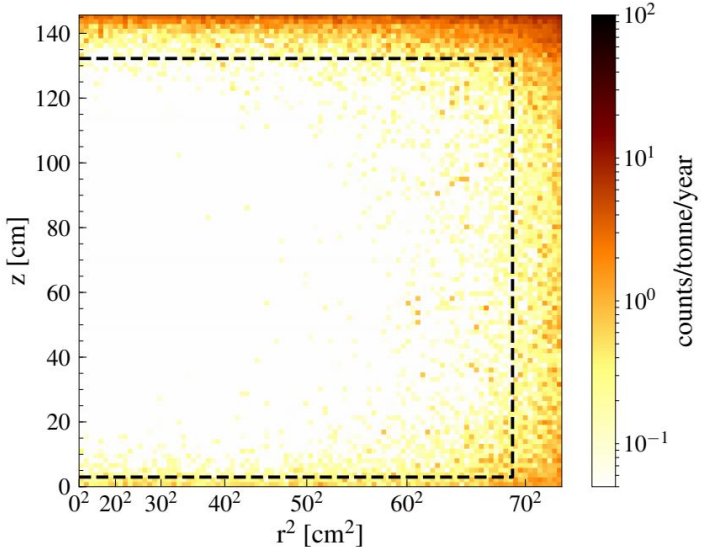
Central 5.6t of xenon defined as radio-quiet “fiducial volume”

Presence of outer detector allows definition at 80% of active volume (vs 45% w/o)

No Veto



After Veto



Expected BG NR cts / 1000 days in 5.6t FV in 6-30keV$_{nr}$:

10.43

1.03

Expected backgrounds

5.6t fiducial volume, 1000 live-days
1.5-6.5 keV_{ee} (6-30 keV_{nr})
single scatters, anti-coincidence with vetoes

Background source	ER [cts]	NR [cts]
Detector components	9	0.07
Dispersed Radionuclides — Rn, Kr, Ar	819	-
Laboratory and Cosmogenics	5	0.06
Surface Contamination and Dust	40	0.39
Physics Backgrounds — 2β decay, neutrinos	322	0.51
Total	1195	1.03
After 99.5% ER discrimination, 50% NR efficiency	5.97	0.51